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Modelling non-exhaust emissions of PM_{10} in Oslo

Impact of the environmental speed limit using the NORTRIP model

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Scientific report

Preface

This report was requested by the Norwegian Public Roads Administration (Statens vegvesen) to provide information concerning non-exhaust traffic emissions in Oslo and the impact of the environmental speed limits on PM_{10} concentrations. This report provides the results of calculations made with the EPISODE dispersion model coupled to the the NORTRIP road dust emission model, a recently developed model for calculating non-exhaust emissions. The NORTRIP model was developed at NILU in conjunction with institutes from Sweden, Denmark and Finland during the NORTRIP project, funded by the Norwegian Environment Agency (Miljødirektoratet) and the Nordic Council of Ministers (NMR).

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Sammendrag

Ikke-eksos trafikkutslipp er en dominerende bidragsyter til konsentrasjoner av PM_{10} både i Norge og andre nordiske land. Utslippene er sterkt knyttet til bruk av piggdekk, men bidrag kommer også fra sand og grus i tillegg til dekk- og bremseslitasje. Flere tiltak har blitt satt i verk for å begrense utslippene, men virkningen av dem må bli kvantifisert bedre for å sikre en effektiv implementering. I denne rapporten benyttes utslippsmodellen NORTRIP for å beregne ikke-eksosutslipp. Modellen blir brukt for å vurdere effekt av endret kjøretøyshastighet relatert til miljøfartsgrensa i Oslo.

Denne rapporten etterfølger en rapport som så på effekt på PM_{10} utslipp og konsentrasjoner ved endret piggdekk- og tungtransportandeler i tillegg til vinterdrift og rengjøringsaktiviteter i Oslo (Denby, 2013).

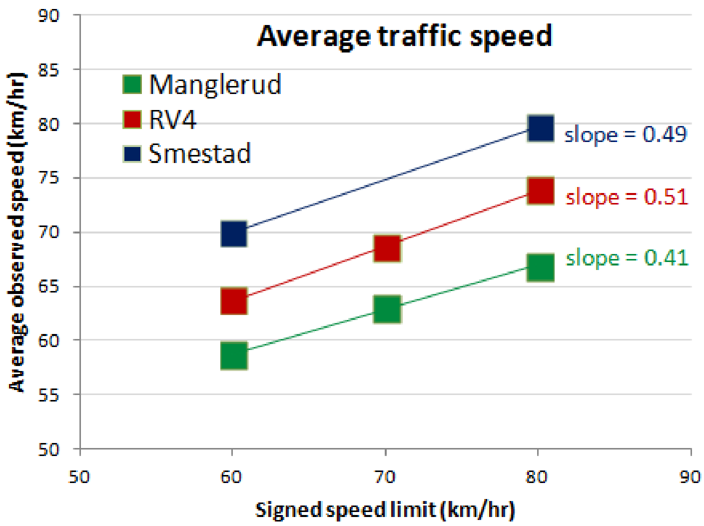
Formålet med denne studien er å vurdere effekt av Miljøfartsgrensa (referert til i grafer og tabeller som ESL, 'environmental speed limit') på PM_{10} konsentrasjonene i Oslo. Miljøfartsgrensa ble introdusert som en reduksjon i skiltet hastighet fra 80 til 60 km/t i piggdekksesongen (november til april) og ble innført i 2004 (RV4), 2006 (ring 3) og 2007 (E18). Siden 2011 har den skiltede hastigheten på miljøfartsgrensestrekningene blitt satt til 70 km/t året rundt. I år, 2013, er det igjen planlagt å senke fartsgrensen til 60 km/t på vinteren mens sommerhastigheten forblir 70 km/t.

Effekten av disse endringene i fartsgrenser blir vurdert med veistøvmodellen NORTRIP, som er en matematisk modell som beskriver veislitasje, blant annet fra piggdekk. Modellen beskriver også oppbygging av støvlager på veioverflaten under våte eller isete forhold, og den påfølgende frigjøringen med oppvirvling av dette støvlageret når veiene tørker.

Veislitasje og oppvirvling har blitt studert både på vei og i laboratorier og det er vist at begge prosessene er ganske lineære med økende fart. Dette betyr at hastighetsreduksjon kan være et tiltak for å redusere utslippene. Det er derimot også mange andre faktorer som påvirker utslippene som antall biler med piggdekk, antall tunge biler, meteorologiske forhold og vinterdrift som salting, støvbinding og feiing.

I denne rapporten brukes utslippsmodellen NORTRIP. Utslipp fra alle andre kildegrupper er hentet fra NILUs utslippsdata for Oslo for å beregne PM_{10}-konsentrasjonene i Oslo for 2008, 2009 og 2010. Modellresultatenes følsomhet overfor hastighetsendring er belyst ved å beregne konsentrasjoner med hastighet 60 km/t og 70 km/t for veier der vinterfartsgrense har vært brukt. Konsentrasjoner er beregnet i fire punkter som reflekterer målestasjoner langs miljøfartsgrensestrekningene (Manglerud, RV4, Smestad and Hjortnes) for alle 3 år. Konsentrasjonskart er laget for å vise konsentrasjonsfordelingen i tillegg til den romlige endringen av økt fartsgrense.

Trafikkdataanalyse
Fordi kjøretøyshastighet er en viktig faktor for veistøvutslipp, er det nødvendig å finne ut hvordan hastigheten faktisk endres ved endret skilting. Trafikktellinger og fartsmålinger utført ved Manglerud, RV4 og Smestad i 2008, 2010 og 2012 har blitt analysert for å bestemme kjøretøyshastighet med kobling til fartsgrenser og trafikkmengder. Analysen viser at senket fartsgrense ikke senker reel kjøretøyshastighet like mye. En reduksjon på skiltene med 10 km/t ga en reel endring på kun 4.7 km/t for disse veiene.



Figur A: *Gjennomsnittlig observert kjøretøyshastighet for de tre trafikktellepunktene som en funksjon av skiltet hastighet.*

Validering av modellen og kildebidrag.
PM_{10} konsentrasjonene er beregnet for 2008, 2009 og 2010 i Oslo med utslipp beregnet for alle utslippskilder. Utslippskildene inkluderer vedfyring, skip, eksos, industri, jordbruk, og andre mobile kilder. NORTRIP modellen er brukt for å beregne ikke-eksos bidraget. Beregnet konsentrasjon blir sammenlignet med observasjoner for ni punkter tilsvarende målestasjoner i Oslo, der fire er veistasjoner langs veier med miljøfartsgrense (Manglerud, RV4, Smestad and Hjortnes).

Sammenligning med observasjoner fra 9 målestasjoner for de 3 årene viser en gjennomsnittlig modellfeil på -12% med et spenn på -30% til +10% for de enkelte stasjonene. Modellert feil for antall overskridelsesdøgn (døgn med gjennomsnitt av PM_{10} på over 50 µg/m^3) er større enn for langtidsmiddelet; Modellen overestimerer antall overskridelsesdøgn for alle observasjonspunktene med 17 % og opp til 40% for enkelte stasjoner. Det er beregnet at ikke-eksos utslipp bidrar med 33 % av konsentrasjonen i gjennomsnitt for de 9 stasjonene, mens eksos bidrar med 13%. Regional bakgrunn bidrar også vesentlig med rundt 32 % av totalen.

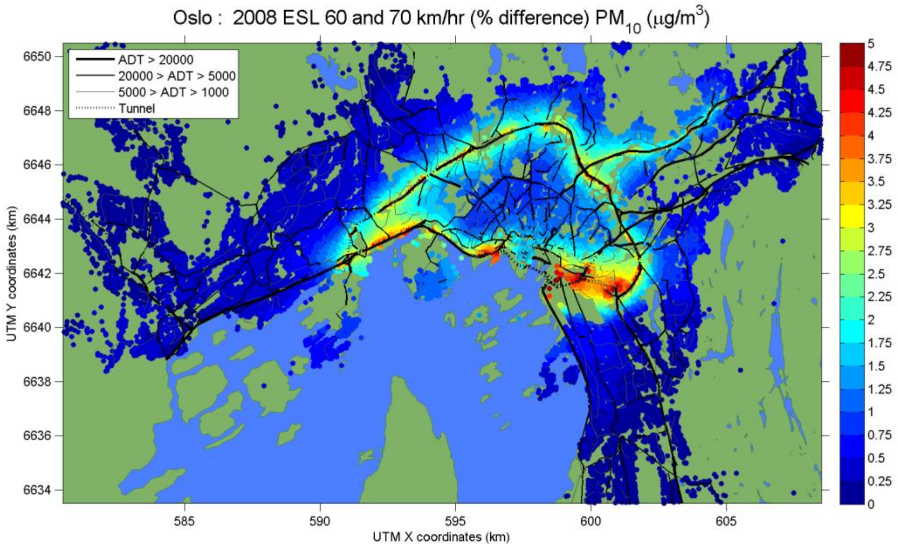
For de fire stasjonene langs miljøfartsgrensestrekningene finner man at modellen underestimerer med 10 % for årsgjennomsnittet mens overskridelsesdøgn er overestimert med 9 %, se tabell A1. Variasjonen fra år til år blir fanget opp av modellen på en riktig måte.

Tabell A: Oversiktstabell for modellvalideringen ved stasjonspunkt langs miljøfartsgrensestrekningene med skiltet miljøfartsgrense på 60 km/t som inngangsdata til NORTRIP. Resultatet er presentert for hvert år som et snitt for de fire stasjonspunktene Manglerud, RV4, Smestad og Hjortnes.

Periode	**Beregnet med skiltet hastighet**		**Observert**	
	Årsgjennomsnitt ($\mu g/m^3$)	Overskridelsesdøgn (døgn)	Årsgjennomsnitt ($\mu g/m^3$)	Overskridelsesdøgn (døgn)
2008	24.9	20	26.7	16
2009	22.4	15	24.9	15.5
2010	19.8	13.2	22.8	12.7
Snitt	**22.4**	**16.1**	**24.8**	**14.7**

Effekt av miljøfartsgrensa på PM_{10} konsentrasjoner

Følsomheten til PM_{10} konsentrasjonene av en fartsgrenseendring fra 60 til 70 km/t i vinterstid er vurdert på to måter. For det første ved å anta en hastighetsendring på 10 km/t og så ved å benytte en endring på 4.7 km/t, basert på den reelle endringen ut i fra observasjoner. Beregningene viser da at årsgjennomsnittet, ved de 4 målestasjonene langs veier med miljøfartsgrense, øker i snitt med 0.74 $\mu g/m^3$ (3.4%) for det første tilfellet og 0.34 $\mu g/m^3$ (1.5%) for det andre tilfellet. Tilsvarende gir snittet for beregningene av overskridelsesdøgn en økning på 3.5 døgn (19%) og 1.8 døgn (8%) for de to hastighetsalternativene. Kartfremstilling av den relative endringen for årsgjennomsnittet med en 10 km/t miljøfartsgrenseendring er vist under.



Figur B: *Relativ endring i årsgjennomsnittet for PM_{10} på grunn av økning i miljøfartsgrense fra 60 til 70 km/t, beregnet for hjemstedsadresser i Oslo for 2008. Enhet i prosent (%).*

Sammenligning med andre veistøvdempende tiltak.

Følsomhetstester av modellen utført for 2009 som er beskrevet i tidligere rapport (Denby, 2013), viser at 1.5% - 3% reduksjon av antall biler med piggdekk vil gi tilsvarende endring som senking av miljøfartsgrensa fra 70 til 60 km/t. Følsomheten til tungtransportandeler ble også vurdert og en reduksjon av tunge biler med 10 % ville lede til en reduksjon på 2 % (0,4 µg/m^3) for årsgjennomsnittet og en reduksjon av antall overskridelsesdøgn med 1,2, se tabell B.

Usikkerheter og variabilitet.

Forskjellen i årsgjennomsnittet og antall overskridelsesdøgn for de fire målestasjonene langs veier med miljøfartsgrense (i 2008, 2009 og 2010) varierte med typisk ±1.1 µg/m^3 og ±1.2 døgn. Fordi trafikkmengdene var ganske konstante for de ulike årene er denne variabiliteten mest sannsynlig en konsekvens av ulik meteorologi. I tillegg til variabiliteten pga. meteorologien varierer den regionale bakgrunnen med en tilsvarende størrelse på rundt ±1.0 µg/m^3 for årsgjennomsnittet. For de beregnede årene varierte bakgrunnen som er benyttet derimot med mindre enn ±0.2 µg/m^3.

Usikkerheter i modellresultatene er blitt vurdert ved en sammenligning med målte konsentrasjoner. Sammenligningen viser at usikkerheten er ±20% for gjennomsnittskonsentrasjonen for enkelte stasjoner mens den er rundt ±40% for overskridelsesdøgn. Tilsvarende kan man bruke disse relative usikkerhetene for å gi en vurdering av usikkerheten for modellfølsomheten knyttet til endret kjøretøyshastighet.

Konklusjon

Modellfølsomheten til kjøretøyshastighet er sammenlignet med andre støvreduserende tiltak som det er gjort beregninger for tidligere (Denby, 2013). Resultatet indikerer at en miljøfartsgrenseendring fra 70 til 60 km/t har tilsvarende effekt som om 1.5 til 3 % færre av bilene har piggdekk eller reduksjon av tunge biler med rundt 10 %, se tabell. Bemerk også at ulik meteorologi og regional bakgrunnskonsentrasjon fra år til år gir like stor eller større endring for PM konsentrasjonene enn fartsgrenseendringen.

Tabell B: Tabell over modellert effekt av hastighet og andre parametere på årsgjennomsnitt og overskridelsesdøgn, inkludert estimat av usikkerheter. Observert variabilitet pga. meteorologi og regionale bakgrunnskonsentrasjoner er også vist.

Parameter	**Endring**	**Endring av konsentrasjon og usikkerhet (µg/m^3)**	**Endring i antall overskridelsesdøgn og usikkerhet (døgn)**
Hastighet (fartsgrense)	70 til 60 km/t (- 10 km/t)	- 0.74 ±0.15	- 3.5 ±1.4
Hastighet (reell hastighet)*	68.7 til 64 km/t (- 4.7 km/t)	- 0.34 ±0.07	- 1.8 ±0.7
Piggdekkandeler*	16% til 14% (- 2%)	- 0.50 ±0.15	- 1.6 ±0.6
HDV andeler*	10% reduksjon av tungtrafikken	- 0.40 ±0.2	- 1.2 ±0.6
Snitt i målt konsentrasjon	Årlig variabilitet pga meteorologi	± 1.1	± 1.2
Regional bakgrunnskonsentrasjon	Årlig variabilitet	± 1.0	Ikke vurdert

*Fra tidligere studie (Denby, 2013), kun for år 2009
*Se figur A.

Vi kan konkludere med at PM_{10} konsentrasjonene vil endres med -0.3 til -0.8 µg/m^3 for årsgjennomsnittet og med -1.5 to -4.0 døgn for antall overskridelsesdøgn med en reduksjon av miljøfartsgrensa fra 70 til 60 km/t. Dette er tatt i betraktning usikkerheter både knyttet til modellberegningen og kjøretøyshastighet og tallene er resultat av en analyse av beregningsresultater for 4 målestasjonspunkt langs veier med miljøfartsgrense. Modellberegninger for hele Oslo viser derimot at effekten kan være opptil 2 ganger større andre steder langs miljøfartsgrensestrekningene. Merk at en slik endring kan være betydelig sett i sammenheng med nasjonale mål og kriteriene for rød luftsone med kun 7 tillatte overskridelsesdøgn. Når det kommer til helseeffekter finnes det heller ikke en nedre grense av PM hvor helseeffekter ikke lenger observeres. Faktisk er forholdet mellom reduksjon av konsentrasjonene og helsegevinsten lineær slik at enhver reduksjon vil kunne gi god helseeffekt, spesielt i tett befolkete områder som i Oslo.

Executive summary

Non-exhaust traffic emissions are a dominant contributor to PM_{10} concentrations in Norway as well as other Nordic countries. These emissions are largely related to the use of studded tyres, but additional contributions come from the application of sand or gravel for road traction and from other wear sources such as brake and tyre. A range of measures have been introduced to reduce these emissions but the impact of the measures needs to be better quantified if they are to be efficiently implemented. In this report the NORTRIP road dust emission model is applied to calculate non-exhaust PM_{10} emissions from traffic in Oslo and to assess the sensitivity of these calculated emissions to vehicle speed, related to the implementation of the environmental speed limits in Oslo.

This report follows a previous report that investigated the impact of studded tyre share, heavy duty vehicle share and road maintenance activities on PM_{10} emissions in Oslo (Denby, 2013).

The aim of this study is to assess the impact of the environmental speed limit (ESL) on PM_{10} concentrations in Oslo. The environmental speed limit was introduced in 2004 (RV4), 2006 (Ring 3) and 2007 (E18), where signed speed limits were reduced from 80 to 60 km/hr during the studded tyre season (November to April). Since 2011 these signed speed limits have been set to 70 km/hr all year round. This year, 2013, the winter time speed limit is planned to be reduced again to 60 km/hr, whilst retaining the summer speed limit of 70 km/hr.

The impact of these changes in speed limit are assessed using the NORTRIP road dust emission model, a mathematical model that describes the road wear that occurs through the use of studded tyres. The model also describes the accumulation of road dust on the surface during wet or freezing periods and the subsequent suspension of the dust into the air when the road surface dries. Road wear and road dust suspension have been studied in both the field and the laboratory and it has been shown that these processes increase roughly linearly with increasing speed. As a result vehicle speed becomes a method for controlling road dust emissions. However, there are other factors influencing these emissions, including the number of cars with studded tyres, the number of heavy duty vehicles, the meteorological conditions and road maintenance activities such as salting, dust binding and cleaning.

In this report we apply the NORTRIP road dust emission model, together with all other modelled emission sources, to model PM_{10} concentrations in Oslo for the years 2008, 2009 and 2010. The sensitivity of the modelled PM_{10} concentrations to a change in vehicle speed is assessed by increasing the winter time environmental speed limit from 60 to 70 km/hr. The resulting concentrations are calculated at four ESL air quality monitoring sites (Manglerud, RV4, Smestad and Hjortnes) for the three years and maps are produced to indicate the spatial distribution of PM_{10} concentrations and the impact of these changes.

Traffic data analysis

Because vehicle speed is an important factor affecting the road dust emissions, it is necessary to determine how actual vehicle speeds vary as a result of changes in signed speed limits. Traffic counts and vehicle speed measurements carried out at the sites Manglerud, RV4 and Smestad for the years 2008, 2010 and 2012 have been analysed to assess vehicle speeds and their dependency on speed limit and traffic volume. The analysis indicates that a change in signed speed limit does not result in an equivalent change in average traffic speed. We find on average that a 10 km/hr change in signage will result in just a 4.7 km/hr change in traffic speed for these roads.

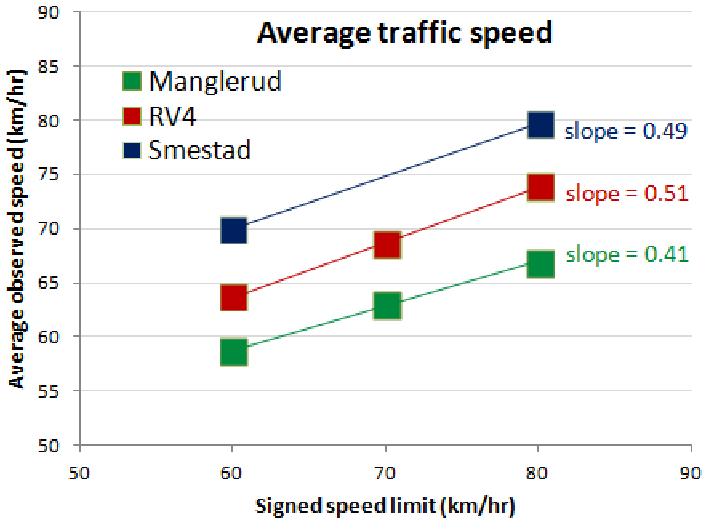


Figure A: Average observed vehicle speeds for the three traffic counting sites shown as a function of signed speed limit.

Model validation and source contributions

PM_{10} concentrations are modelled for the years 2008, 2009 and 2010 in Oslo using all known emission sources. These sources include domestic heating by wood burning, shipping, traffic exhaust, industry, agriculture and mobile combustion sources. The NORTRIP model is used to calculate the contribution of non-exhaust traffic induced emissions. Modelled concentrations are compared to observations at nine air quality monitoring sites in Oslo, four of which are traffic stations placed along ESL roads (Manglerud, RV4, Smestad and Hjortnes).

Comparison with observations at all nine sites over the three years indicates an average model error of -12% with a range of -30% to +10% for the individual stations. The model error in predicting the number of exceedance days (number of days with PM_{10} daily mean concentrations > 50 µg/m^3) is larger than that found for the mean concentrations, with the model overpredicting the total number of exceedance days for all sites by 17% with an error for individual sites of approximately 40%. Based on the model calculations the non-exhaust emissions account for 33% of the observed PM_{10} concentrations, when averaged over the nine available monitoring sites, compared to exhaust emissions that contribute with 13%. The other major contribution comes from the regional background, at around 32% of the total observed.

For the four ESL sites we find that the annual mean concentrations are underpredicted by 10% and the average number of exceedance days is overpredicted by 9%, see table below. The model correctly follows the observed changes from year to year.

Table A: Summary table of the model validation at the ESL sites using the signed environmental speed limit of 60 km/hr as vehicle speed input to NORTRIP. Results are presented for each year as an average at the ESL sites Manglerud, RV4, Smestad and Hjortnes.

Period	**Modelled using signed speed limit**		**Observed**	
	Annual mean ($\mu g/m^3$)	Exceedance days (days)	Annual mean ($\mu g/m^3$)	Exceedance days (days)
2008	24.9	20	26.7	16
2009	22.4	15	24.9	15.5
2010	19.8	13.2	22.8	12.7
Average	**22.4**	**16.1**	**24.8**	**14.7**

Impact of the environmental speed limit on PM_{10} concentrations

The sensitivity of PM_{10} concentrations to a change in winter time environmental speed limit, from 60 to 70 km/hr, is assessed in two ways. Firstly by assuming that the actual traffic speed also changes by 10 km/hr and secondly that the actual traffic speed changes more realistically by just 4.7 km/hr. The results indicate that annual mean PM_{10} concentrations (assessed at the four ESL sites) increase by an average of 0.74 $\mu g/m^3$ (3.4%) for the first case and by 0.34 $\mu g/m^3$ (1.5%) for the second case. Similarly the average number of exceedance days increases by 3.5 (19%) and 1.8 days (8%) for the two cases respectively. A map showing the relative change in annual mean concentrations as a result of a 10 km/hr change in vehicle speeds on ESL roads is shown below.

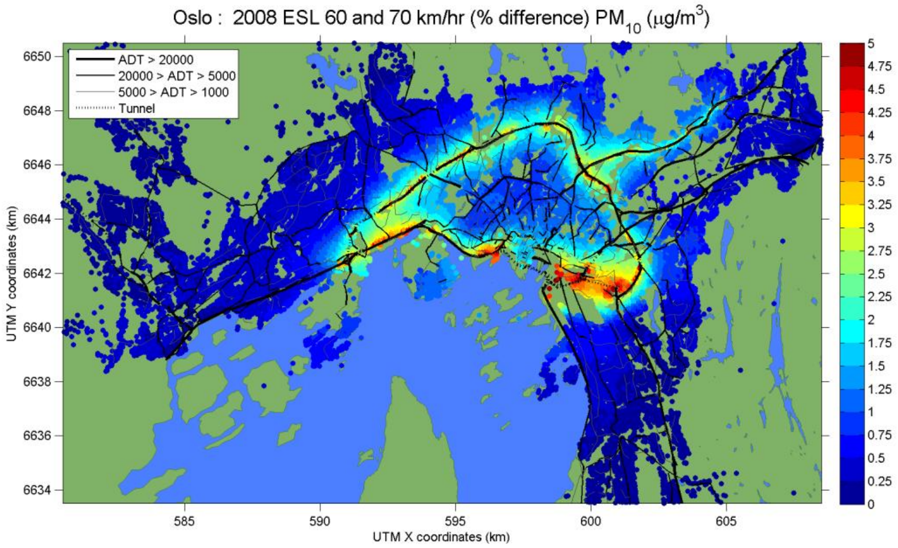


Figure B: Relative change in annual mean PM_{10} concentrations as a result of an increase in ESL from 60 to 70 km/hr, calculated at home addresses in Oslo for the year 2008. Units are in percent (%).

Comparison to other road dust reduction measures

Sensitivity tests of the model, carried out for 2009 in a previous report (Denby, 2013), show that a 1.5% - 3% reduction in the number of cars using studded tyres would be equivalent to the reduction obtained by reducing the winter time speed limit from 70 to 60 km/hr. The sensitivity of the model to the number of heavy duty vehicles (HDV) was also assessed in the same report for 2009. According to those results a reduction in the HDV traffic of roughly 10% would lead to a comparable decrease of 2% (0.4 µg/m^3) in the annual mean concentrations and a reduction in the number of exceedance days of 1.2 days, see table B. Note that general reductions in studded tyre share or HDV have a much broader impact, throughout all of Oslo, than do speed reductions on a limited number of roads.

Uncertainties and variability

The typical difference in annual mean concentrations and number of exceedance days at the four ESL sites (for the years 2008, 2009 and 2010) is found to be ±1.1 µg/m^3 and ±1.2 days respectively. Since traffic volumes are fairly constant from year to year this variability is likely due to the different meteorological conditions. In addition to the variability in the meteorology we also see that annual mean regional background concentrations can vary by a similar amount, approximately ±1.0 µg/m^3. For the years presented in this report the regional background concentrations varied by less than ±0.2 µg/m^3.

Uncertainty of the model results has been assessed by comparison with the available monitoring data. This indicates a level of uncertainty in the mean concentrations, at individual sites, to be approximately ±20% and in the number of exceedance days to be around ±40%. These same relative uncertainties can be used to indicate the uncertainty of the model sensitivity to changes in vehicle speed.

Conclusion

The sensitivity of the model to changes in vehicle speed is compared to model calculations previously carried out by Denby (2013), see table below, that address other traffic parameters affecting road dust emissions. These results indicate that a reduction in the environmental speed limit from 70 to 60 km/hr has a similar impact as a reduction of 1.5 - 3% in the number of cars using studded tyres or a decrease in the number of heavy duty vehicles of around 10%. We also note that the inter-annual variability due to meteorology and regional background concentrations is generally as large, or larger, than the change introduced by changes in speed limit.

Table B: Table showing the impact of speed and other traffic parameters on the modelled annual mean concentration and the number of exceedance days, including an estimate of the uncertainty. Also included is the observed variability due to meteorology and regional background concentrations.

Parameter	**Change in parameter**	**Change in concentration and uncertainty (µg/m^3)**	**Change in exceedance days and uncertainty (days)**
Traffic speed (speed limit)	70 to 60 km/hr (- 10 km/hr)	- 0.74 ±0.15	- 3.5 ±1.4
Traffic speed (real speed)	68.7 to 64 km/hr (- 4.7 km/hr)	- 0.34 ±0.07	- 1.8 ±0.7
Studded tyre share*	16% to 14% (- 2%)	- 0.50 ±0.15	- 1.6 ±0.6
HDV share*	10% decrease in HDV traffic volume	- 0.40 ±0.2	- 1.2 ±0.6
Average observed concentrations	Inter-annual variability due to meteorology	± 1.1	± 1.2
Regional background concentrations	Inter-annual variability	± 1.0	Not assessed

*From the previous study from Denby (2013) for the year 2009 only

By taking into account uncertainties in model calculations and in traffic speeds we conclude that the change in air quality for PM_{10} due to a reduction in environmental speed limit from 70 km/hr to 60 km/hr is likely to be in the range from -0.3 to -0.8 µg/m^3 for the annual mean concentrations and from -1.5 to -4.0 days for the average number of exceedance days. This result is valid for the monitoring sites addressed in this study along the environmental speed limit roads. Additional model assessment for all of Oslo indicates that the impact can be larger at other sites along the environmental speed limit zone, by up to a factor of two.

Impact of the environmental speed limit using the NORTRIP model

1 Background and introduction

Non-exhaust emissions are the dominant contributor to PM_{10} concentrations in many Nordic countries. These emissions are largely related to the use of studded tyres but additional contributions come from the application of sand or gravel during the winter as well as from salt. Other wear sources such as brake and tyre wear also contribute.

To reduce the non-exhaust emissions a number of abatement strategies have been introduced in Norwegian cities. These include:

- the reduction of vehicles using studded tyres through fees and public awareness
- the reduction of vehicle speeds using environmental speed limits
- the use of dust binding salts ($MgCl_2$) to keep road surfaces moist
- road cleaning activities

All these strategies come with a monetary cost and may vary in their effectiveness. Quantifying their effectiveness is often difficult and may be based on indicative information rather than on any quantifiable method. In general measures are assessed to be successful if they achieve their aims of compliance with air quality legislation. Assessment of monitoring data in Oslo in the years before and after measures were introduced (Gjerstad et al., 2012) indicate that measures currently in place do have an impact, but exactly how much is due to each individual measure is not known. Some quantification has been carried out however. In one case a measurement campaign was established at Riksvei 4 in Oslo over a two year period (2004-2005) to measure the impact of speed reduction on PM_{10} emissions (Hagen et al., 2005). This campaign indicated that speed reduction was an effective method for reducing road wear emissions.

To help quantify the impact of mitigation strategies related to non-exhaust traffic emissions on air quality, efforts have been made to develop models that can be applied to assess air quality management strategies. During the NORTRIP project (Johansson et al., 2012), a co-operative project between four Nordic countries, a comprehensive non-exhaust emission model was developed at NILU (Denby and Sundvor, 2012). This model provides the potential for assessing abatement strategies and understanding the impacts of both traffic and meteorological conditions. Though the model is still under development there are a number of applications for which it can be used and which provide insight into the processes affecting non-exhaust emissions.

In a previous report produced by NILU for the Norwegian road traffic authorities (Denby, 2013) the NORTRIP model was applied for three years (2004-2006) at RV4 and for two years (2008-2009) for all of Oslo. In the first case comprehensive input data was available to assess and validate the model during the speed reduction experiment carried out at RV4. In the second case the

NORTRIP model is included in the general calculations of PM_{10} concentrations for all of Oslo, which includes all other emission sources. After application the model was then used to determine the sensitivity of the non-exhaust emissions, and concentrations, to a number of parameters. These include the fraction of vehicles using studded tyres, the number of heavy duty vehicles and the impact of salting, dust binding and cleaning.

In this second report we build upon these previous calculations and assess the impact of the environmental speed limit on PM_{10} concentrations in Oslo. These speed limits were introduced in 2004 (RV4), 2006 (Ring 3) and 2007 (E18), where signed speed limits were reduced from 80 to 60 km/hr during the studded tyre season (November to April). Since 2011 these signed speed limits have been set to 70 km/hr all year round. This year, 2013, the winter time speed limit will again be reduced to 60 km/hr, whilst retaining the summer speed limit of 70 km/hr. In order to assess the impact of vehicle speed on concentrations, calculations are carried out for the years 2008, 2009 and 2010 using both 60 and 70 km/hr winter time environmental speed limits.

Since the road wear and suspension rates in the NORTRIP model are linearly dependent on vehicle speed, changes in vehicle speed will impact on the calculated emissions. However, signed speed limits do not necessarily represent actual vehicle speeds and information on the actual vehicle speeds in Oslo needs to be analysed. For this reason effort is made, prior to the model calculations, to determine a relationship between real vehicle speeds and signed speed limits using measured traffic flows.

The model calculations carried out for this report are based in previous work in the NORTRIP and TRANSPHORM (www.transphorm.eu) projects in which NILU is involved and are a continuation of the previous report from Denby (2013).

2 Overview of the NORTRIP model

The NORTRIP model calculates the non-exhaust traffic induced emissions and is described and applied in detail in Denby et al. (2013a, 2013b) and Denby and Sundvor (2012). The model uses the mass balance approach for both road dust and for road surface moisture. As such it is split into two sub-models, one for dust and one for moisture, and these are coupled. An overview of the processes described in the model is given in Fig. 1.

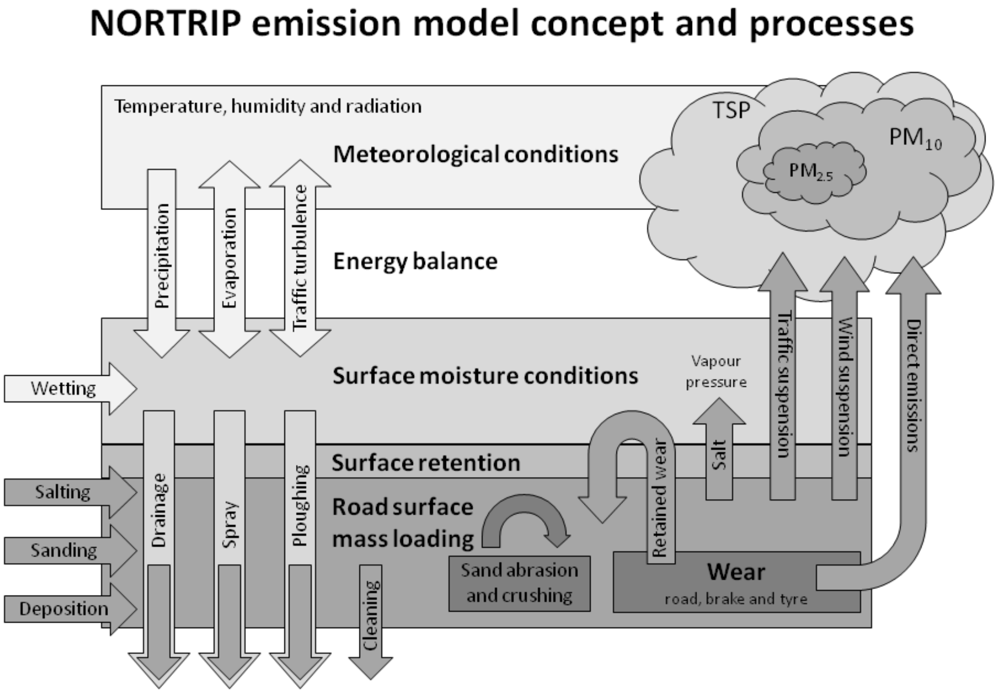


Figure 1: NORTRIP model concept showing the full model processes. Sand abrasion and crushing, as well as windblown suspension, are not included in the current application.

For the road dust sub-model the following major processes are included:

- Road wear based on the Swedish road wear model (Jacobson and Wågberg, 2007)
- Wear and emission of tyre and brake sources
- Direct emission of PM as well as retention of PM on the surface due to surface moisture
- Suspension of accumulated wear during dry periods
- Differentiation between the light and heavy duty contributions to wear and suspension
- Mass balance and suspension of salt
- Mass balance and suspension of sand (not included in this application)
- Removal processes for dust and salt (particularly salt) including drainage, vehicle spray, cleaning and snow ploughing
- Salting and sanding model for generating salt and sand application to the road, if no information is available

For the surface moisture sub-model the following main processes are included:

- Addition of water and/or ice to the surface through precipitation and wetting during salting/sanding activities

- Removal of water through drainage and vehicle spray
- Removal of snow through snow ploughing
- Energy balance model predicting surface temperature, surface melt/freezing and surface evaporation/condensation of moisture
- Impact of salt on the surface freezing temperature and on vapour pressure. Allows for the inclusion of ‘dust binding’ salts ($MgCl_2$).

Though there are a large number of model parameters defined, we provide in Table 1 a short summary of the total wear rates, the PM_{10} fraction of total wear and the vehicle induced suspension rates used in this application. The values are relevant for a vehicle speed of 70 km/h and the wear and suspension rates are taken to be linearly dependent on vehicle speed. Total road wear is determined for studded tyres using the Swedish road wear model (Jacobson and Wågberg, 2007). Total tyre and brake wear, as well as non-studded road wear, is calculated based on literature, e.g. Boulter (2005). PM size fractions for wear particles are based on literature and experimental data, e.g. Snilsberg et al. (2008), and on the application of the model to a range of datasets (Denby et al. 2013a; 2013b; Denby and Sundvor, 2012).

Table 1: Total wear rates, road dust suspension rates and PM_{10} fraction of wear and suspension for light duty vehicles used in the NORTRIP model. Wear and suspension rates for heavy duty vehicles are considered to be 5 and 10 times larger respectively than for light duty vehicles. The reference speed for these parameters is 70 km/h.

	Studded tyres	**Winter tyres**	**Summer tyres**	**PM_{10} fraction of wear (%)**
Road wear (g km^{-1} veh^{-1})	3.8	0.15	0.15	21
Tyre wear (g km^{-1} veh^{-1})	0.10	0.10	0.10	10
Brake wear (g km^{-1} veh^{-1})	0.01	0.01	0.01	80
Road dust suspension rate (veh^{-1})	$1.0x10^{-6}$	$1.0x10^{-6}$	$1.0x10^{-6}$	21

3 Analysis of vehicle speeds

Since vehicle speed is an important input parameter for the NORTRIP model it is necessary to analyse existing information concerning the relationship between vehicle speed and signed speed limits (SL), as these two are not necessarily the same. In addition there is a need to estimate the real world change in speed with a change in speed signage.

To this end measured traffic data has been provided by Statens Vegvesen at sites corresponding to the air quality measurement sites of Manglerud, RV4 and Smestad. The analysis looks at the following:

1. The relationship between observed average vehicle speed and signed speed limit
2. The change in observed speed resulting from a change in signed speed limit

3. Development of a functional relationship between traffic volume, signed speed limit and the observed vehicle speed

3.1 Analysis of raw data

The raw data consists of traffic counts and average vehicle speeds per lane. Winter (November – March) and summer (May – October) months were split for analysis to separate the different speed signage. April was excluded from the analysis since the transition between speed signage often occurred in this month. For the Smestad data only 4 months were available each year. The traffic data provided covers the sites and periods listed in Table 2. Also included in this table are the average daily traffic (ADT), the fraction of heavy duty vehicles (length > 7.5 m), the signed speed limit and the average vehicle speeds per season.

Fig. 2 - 4 present the raw and analysed data for the winter period 2008 at Manglerud, RV4 and Smestad respectively. In these figures the speed is plotted as a function of average hourly traffic per lane (top left) for the inward and outward bound traffic as well as for the total traffic. These data are then binned and averaged for different traffic volumes (top right). The solid line is the linear fit (see Section 3.3) to these data. Also indicated are the diurnal cycle of traffic flow per lane (bottom left) and traffic speed (bottom right). Included in this last plot is the vehicle speed parameterisation developed in Section 3.3. Similar plots and analysis are made for each year and season for each site.

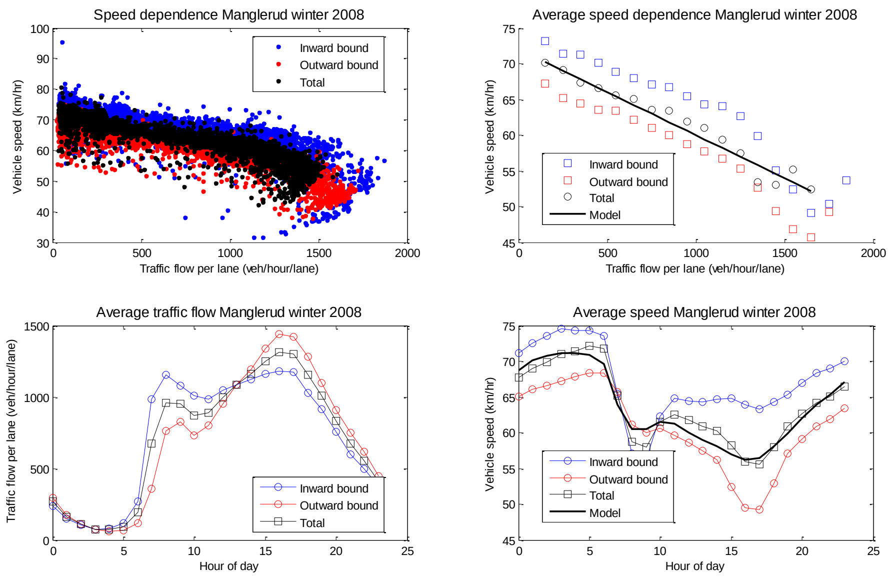


Figure 2: Plots showing the analysis of the raw traffic data for the site Manglerud in the winter of 2008. See text for details.

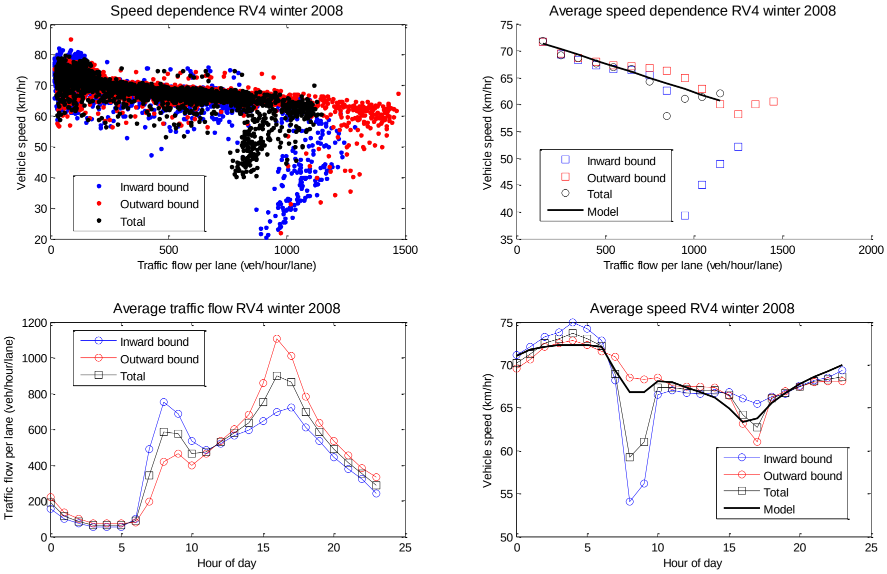


Figure 3: Plots showing the analysis of the raw traffic data for the site RV4 in the winter of 2008. See text for details.

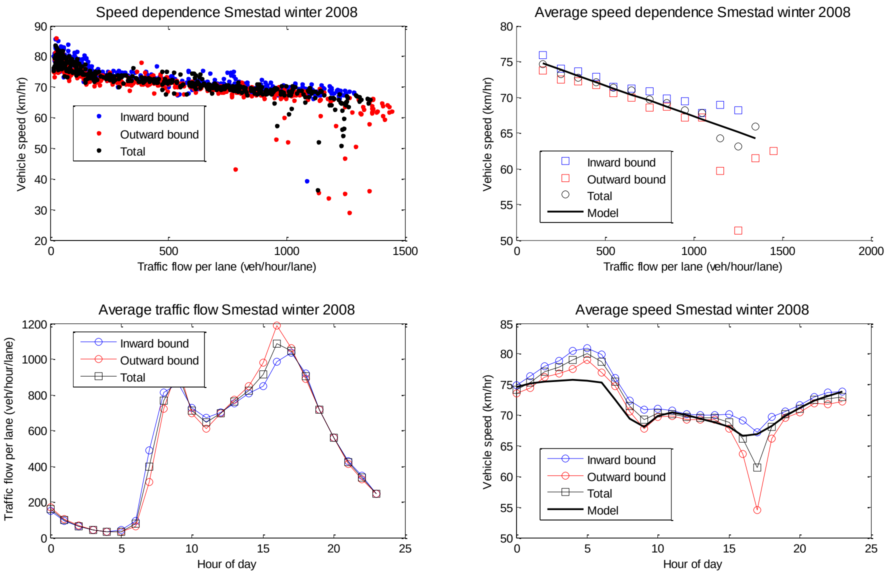


Figure 4: Plots showing the analysis of the raw traffic data for the site Smestad in the winter of 2008. See text for details.

These results can be averaged per site and per signed speed limit and these are shown, along with a linear fit to the data per site, in Fig. 5. Despite the similar signage at the three sites the average traffic speed is highest at Smestad and the lowest at Manglerud. This is a result of the different traffic flow conditions at the three sites. At both RV4 and Manglerud significant congestion occurs in the mornings and afternoons, resulting in reduced speeds. In addition the upward slope of the outbound traffic at Manglerud reduces the traffic speed by 10 km/hr compared to the inward bound speed during free flow conditions.

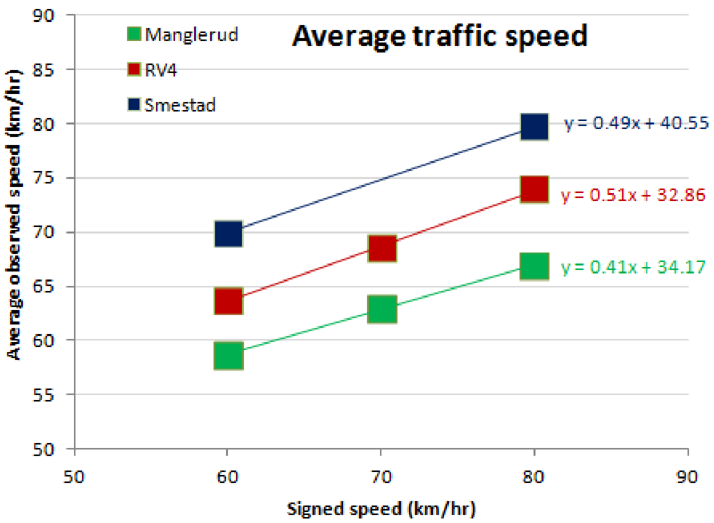


Figure 5: Average observed vehicle speeds for the three traffic counting sites shown as a function of signed speed limit.

In addition to the average speed (V_{av}) we also fit the data to determine the low traffic volume speed (V_{low}), for traffic volumes approaching 0, and the critical traffic speed (V_{crit}), corresponding to an average hourly traffic flow (AHT) of 1500 veh/lane. This is done in order to develop the vehicle speed parameterisation in Section 3.3, used to estimate hourly vehicle speeds based on AHT and speed signage. The parameters V_{low} and are V_{crit} presented in Figs. 6 and 7 show that low traffic volume speeds are similar at the three sites, though speeds at Smestad remain higher. Generally low traffic volume speeds are above the speed signage, particularly for the lower speed limits. The critical traffic volume speed reflects the traffic flow. In this case Smestad has critical speeds that are significantly higher than the other two sites as the traffic flow here is less inhibited.

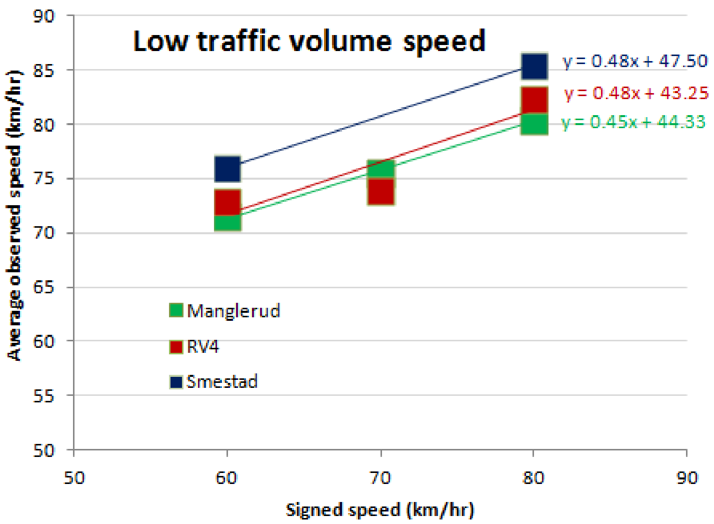


Figure 6: Observed low traffic volume vehicle speeds for the three traffic counting sites.

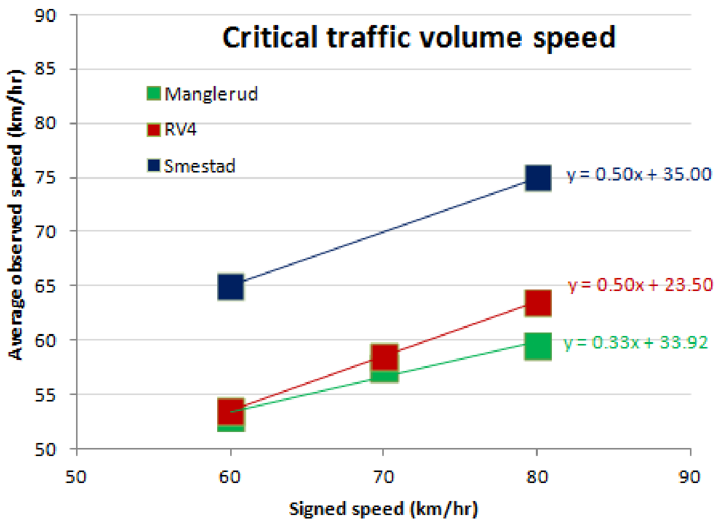


Figure 7: Observed critical traffic volume vehicle speeds for the three traffic counting sites.

Table 2: Summary of the results of the traffic data analysis

Site	**Years**	**Available months**	**ADT (winter /summer)**	**HDV % (summer /winter)**	**Speed limit (winter /summer) km/hr**	**Mean speed (winter /summer) km/hr**
Manglerud	2008	All	68232/72536	7.7/8.2	60/80	59.6/66.9
	2010	All	68228/72537	7.7/8.2	60/80	57.8/66.9
	2012	All	70383/73276	7.5/8.1	70/70	61.5/64.5
RV4	2008	All	40823/43472	4.1/4.5	60/80	65.3/75.0
	2010	All	45367/45612	4.8/5.1	60/80	62.1/72.9
	2012*	All	30369/31610	3.3/4.1	70/70	70.3/66.8
Smestad	2008	1,4,9,12	49734/52596	4.3/5.3	60/80	68.8/79.9
	2010	3,4,5,9	46837/53813	4.5/5.0	60/80	71.1/79.6

* Missing data from lanes during this period

3.2 Observed change in speed with change in signed speed limit

In Figs. 5, 6 and 7 the average, the low traffic volume and the critical traffic volume vehicle speeds are shown for the three sites as a function of signed speed. For each site the gradient of these observed speeds is determined. This indicates the observed change of speed for a change in signage. Despite differences in absolute values the resulting gradients are consistent over the three sites. The results are summarized in Table 3.

These results indicate that the response of traffic to changes in the speed limit is on average 4.7 km/hr for a 10 km/hr change of signed speed. This indicates clearly that changes in speed limits are not reflected in a 1:1 change in actual vehicle speed. This has important consequences for the effectiveness of the environmental speed limits and will be discussed further in Section 4.

Table 3: Summary of the traffic speed sensitivity analysis showing the actual change in vehicle speed parameters given a 10 km/hr change in signed speed limit.

Site	**Change in observed speed per 10 km/hr change in signage**		
	Average (V_{av})	Low traffic volume (V_{low})	Critical traffic volume (V_{crit})
Manglerud	4.1	4.8	3.3
RV4	5.1	4.8	5.0
Smestad	4.9	4.5	5.0
Average	**4.7**	**4.7**	**4.4**

3.3 Development of a vehicle speed parameterisation for use in NORTRIP emission modelling

The NORTRIP model uses hourly vehicle speeds to determine road wear rates, road dust suspension and also to determine road moisture spray. As such it is important to provide the model with the best estimates of actual vehicle speeds. The traffic data currently available for generating traffic related emissions is limited to average daily traffic volume (ADT), heavy duty vehicle fraction (HDV) and signed speed limit (SL) for each road link. Temporal profiles (daily cycle, day of week and week of year) for light and heavy duty vehicles distribute the ADT on an hourly basis providing traffic volumes for each hour of the day. However, no such temporal variation exists for traffic speed and no relationship between signed speed and actual speeds is available. In order to implement more realistic vehicle speeds in the air quality modelling a vehicle speed parameterisation (VSP) is developed based on the average hourly traffic volume per lane (AHT).

The parameterisation is based on a linear relationship between traffic speed and traffic volume, as shown in Figs. 2 - 4 (top right). The vehicle speed (V_{vsp}) is calculated from the average hourly traffic per lane (*AHT*) using:

$$V_{vsp} = V_{low} + AHT \frac{(V_{crit} - V_{low})}{(AHT_{crit} - AHT_{low})} \quad (1)$$

Here V_{low} is the vehicle speed at low traffic volumes ($AHT_{low} \rightarrow 0$) and V_{crit} is the critical vehicle speed at which no further increase in traffic flow is possible, assumed to occur at $AHT_{crit} = 1500$.

The values of the two parameters, V_{low} and V_{crit}, can be determined from measured traffic data, as has been done in Section 3.1, for each road. However, we require a more general formulation that can be used in the traffic emission estimates, which will be based primarily on the speed limit value (V_{SL}) provided for each road link.

With this in mind we generalise the results obtained in Section 3.1. For each available data set V_{low} and V_{crit} are determined by visually fitting to the binned traffic volume data, as shown in Figs. 2 – 4 (top right). These parameters are then averaged for each signed speed at each site and fitted as a linear function of signed speed (Figs. 6 and 7). These fits are then averaged for all three sites to provide linear functions for V_{low} and V_{crit}. As such these parameters are only valid in the range 60 – 80 km/hr but we extend this up to 90 km/hr. To obtain more realistic values below 60 km/hr we extrapolate these values from 60 to 30 assuming the fit passes through 0 km/hr, to get a more realistic functionality for lower speed limits. The relationships for V_{low} and V_{crit} as a function of V_{SL} become:

$$V_{low} = 0.47V_{SL} + 45 \qquad for \;\; 60 < V_{SL} < 90\ (km/hr) \quad (2a)$$

$$V_{low} = \frac{(0.47 \cdot 60 + 45)}{60}\, V_{SL} \qquad for \;\; 30 < V_{SL} < 60\ (km/hr) \quad (2b)$$

$$V_{crit} = 0.44V_{SL} + 31 \qquad for \;\; 60 < V_{SL} < 90\ (km/hr) \quad (3a)$$

$$V_{crit} = \frac{(0.44 \cdot 60 + 31)}{60}\, V_{SL} \qquad for \;\; 30 < V_{SL} < 60\ (km/hr) \quad (3b)$$

We can also make a similar functional relationship for V_{av} though this is not used directly in the parameterisation.

$$V_{av} = 0.47V_{SL} + 36 \qquad for \;\; 60 < V_{SL} < 90\ (km/hr) \quad (4a)$$

$$V_{av} = \frac{(0.47 \cdot 60 + 36)}{60}\, V_{SL} \qquad for \;\; 30 < V_{SL} < 60\ (km/hr) \quad (4b)$$

These parameters, as a function of speed limit, are shown graphically in Fig. 8.

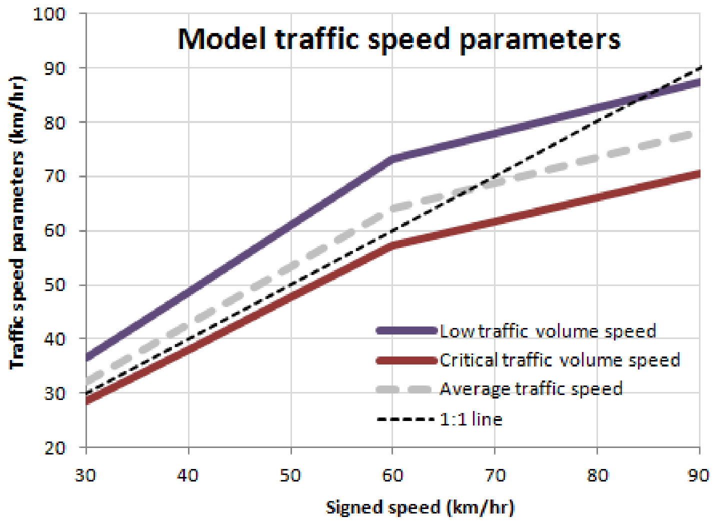


Figure 8: Parameterisation used to determine the parameters V_{low} (low traffic volume speed), V_{crit} (critical traffic volume speed) and V_{av} (average traffic speed) as a function of speed limit (V_{SL}). Dotted line indicates the 1:1 line.

Equations 2 and 3 are then used in conjunction with Equation 1 to determine the traffic speed on an hourly basis for all road links. In this formulation the low traffic volume speeds are higher than speed limits for speed limits < 80 km/hr. In general, but dependent on the actual hourly traffic volume, the average parameterised traffic speeds below 60 km/hr will be higher than the speed limit, as indicated by the measurements (Fig. 5). It is worth noting, in this regard, that the available traffic measurements are from access roads with high traffic volumes and higher speed limits. Driving habits on these roads will tend to be different than on more minor roads with speed limits < 60 km/hr and lower traffic volumes. However, no information on traffic speeds is available for these minor roads.

4 Air quality modelling of PM_{10} in Oslo 2008, 2009 and 2010

In order to assess the total impact of non-exhaust emissions it is necessary to model concentrations for the entire city of Oslo. Recent modelling activities in the EU TRANSPHORM project (www.transphorm.eu) have lead to improvements in both emissions and models in the Oslo region. The NORTRIP model has been included in this modelling in a slightly simplified form, since the original NORTRIP model has been developed for a single road with detailed input data and not for use on more than 10 000 road links without the required input data.

The simplified version of the NORTRIP model calculates the surface moisture for 3 different road types corresponding to heavily trafficked roads, communal roads with low traffic loads and tunnels which are assumed to be dry all the time. In addition the road dust sub-model has been simplified to include removal of road dust only through the processes of suspension and cleaning, which are the two major processes, though removal by spray processes may also be significant on higher speed roads. Salt is included in the moisture model but salt emissions are not included in the road dust model. Road maintenance activity data is taken from roads between Griffenfeldts gate and Marcus Thranes gate on Ring 3 (for 2008 and 2009) and assumed to be applicable to all highways in Oslo. For 2010 no such data were available and so the salting and cleaning rule model, part of the NORTRIP model that predicts road maintenance activities based on meteorological conditions, was applied. All roads are assumed to be snow ploughed.

In Table 4 a number of meteorological and road maintenance parameters are shown for the three years. These parameters are representative of the entire calendar year. We see that average temperatures were progressively lower from 2008 – 2010 and that 2008 was the wettest year. Despite the drier conditions in 2010 the modelled frequency of road wetness was as high in 2010 as it was in 2008, likely due to the cold temperatures that kept the roads frozen or wet (after salting) and reduced evaporation. The higher number of model generated snow ploughing events in 2009 indicate that a larger amount of precipitation came as snow in this year, compared to the other years.

Table 4: Summary of annual meteorological conditions and road maintenance activities for the modelled years.

Parameter	2008	2009	2010
Temperature (C)	7.7	6.6	4.6
Relative humidity (%)	75	77	77
Total precipitation (mm)	875	658	579
Frequency of precipitation (%)	14	7	5
Modelled frequency of wet road (%)	51	45	51
Salting events	112	157	55
Cleaning events	0	20	6*
Snow ploughing events	9*	17*	4*

* Using modelled road maintenance activity rules from NORTRIP

4.1 Model setup

The model is set up in the same configuration as for Denby (2013) but we reiterate this here. The dispersion model applied is the stand-alone version of the EPISODE model, which is the model used in AirQUIS. This model consists of a gridded (1 x 1 km^2) Eulerian model coupled with a Gaussian line source model for modelling the local contribution at receptor points near roads. The model coupling leads to a double counting of the emissions near roads which has been estimated to contribute a maximum increase of 10 - 20% to the model concentrations at near road receptor points. The model domain, the road links and the position of the air quality measurement stations used in the validation are shown in Fig. 9.

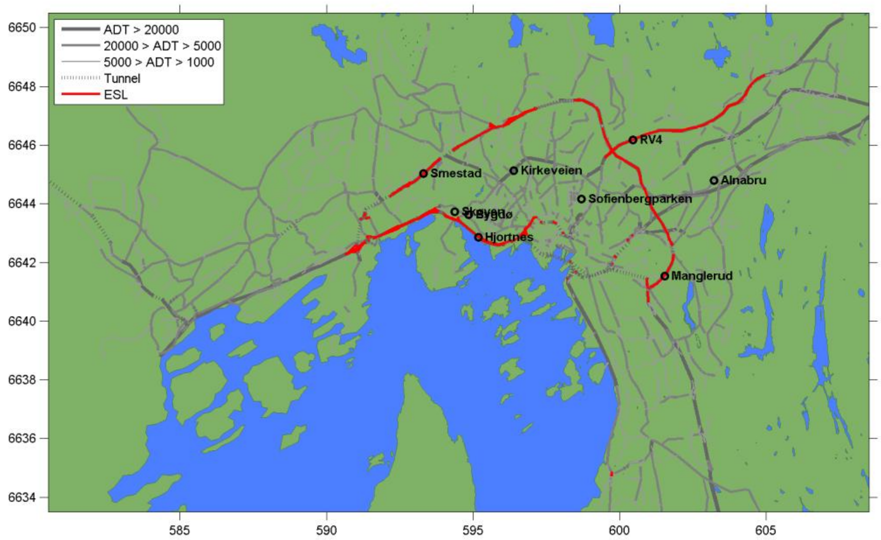


Figure 9: Model domain showing major road links (ADT>1000) and position of the monitoring sites used in the calculations. Road links defined as using the environmental speed limit (ESL) are shown in red.

Meteorology is generated in the model using the diagnostic wind field model MCWIND based on meteorological measurements from Valle Hovin and Blindern. Data used are vertical temperature gradient, wind speed and wind direction.

Emissions are generated for all known sources, these include:

- Traffic non-exhaust emissions (NORTRIP)
- Traffic exhaust emissions
- Domestic heating emissions (temperature dependent)
- Shipping emissions (updated using STEAM2 data)
- Industrial emissions
- Agricultural emissions (updated to include summer emissions)
- Mobile source emissions (updated for new technology)

Regional background concentrations are derived from a combination of data from Birkenes station and from the minimum measured concentration in the model domain over a moving 24 hour window.

Model calculations are made separately for the three calendar years 2008, 2009 and 2010. Maximum studded tyre shares are taken to be 16% for all cars and LDVs and 8% for HDVs for all years. The studded tyre season was kept the same for all years, starting November 1 and ending half way through April. Since the NORTRIP model accumulates dust on the road surface, the emission calculations start in November of the previous year, so that a dust depot can be built up from the start of the studded tyre season.

The NORTRIP model does not account directly for road surface abrasion through sand or gravel on the surface in this application. In Oslo gravel is frequently applied on communal roads and kerbs and is evident on the road surface during the winter and spring periods. To reflect this the wear rates of communal roads are doubled in the model. There is significant uncertainty related to this aspect of the modelling.

Salting and cleaning activities for all of Oslo in 2008 and 2009 are taken from the ISS road maintenance activity data (between Griffenfeldts gate and Marcus Thranes gate). In 2008 no cleaning events were noted in these data but in 2009 a large number were carried out. Cleaning, with a cleaning efficiency of 20% in this case, is included in the model for all highways based on these activities, however this cleaning in 2009 is likely to be an overestimate. According to the ISS activity data no specific dust binding events occurred ($MgCl_2$ only) but $MgCl_2$ in solution was used as a mixture with NaCl according to the normal practise. In 2010 no such data were available and the salting and cleaning rules implemented in NORTRIP were applied. This led to around 55 salting events and 6 cleaning events in 2010.

For the calculations presented here all roads related to the environmental speed limit are given speed limits of 60 km/hr during the studded tyre season and 70 km/hr outside of this season. Assessment of the impact of changes in speed limit are carried out by increasing the speed limit during the studded tyre season to 70 km/hr on these roads.

4.2 Model validation

The model has been validated in Denby (2013) for the years 2008 and 2009 at 9 separate sites including Manglerud, RV4, Smestad and Hjortnes, which are the sites along environmental speed limit roads. This validation was carried out using the signed speed limit as vehicle speed input to the NORTRIP model. For completeness we reproduce a summary of these results, along with the additional year of 2010.

In Figs. 10, 11 and 12 the mean concentrations, number of exceedance days, 36'th highest daily mean concentration (corresponding to the 90'th percentile when all days of the year are available) and daily mean temporal correlation are shown for the years 2008, 2009 and 2010.

The model slightly under predicts the mean concentrations, with an average fractional bias over all stations of -10% (2008), -12% (2009) and -13% (2010). The under prediction occurs mostly during the summer period where the model appears to be missing emission sources. The fractional bias per station ranges from -30% to +10% for all years.

The number of exceedance days varies more significantly from station to station than does the mean concentration. This is true for both modelled and observed concentrations. Manglerud shows the largest error in exceedance days in 2008. Road maintenance activities may not be well represented at this site (no cleaning was undertaken). The number of exceedance days is very difficult to predict as only slight changes in concentrations can have a significant impact on the results. Other predictors, such as the 90'th percentile, or 36'th highest daily mean concentration (also shown in Figs. 10 to 12), are more robust indicators and are more useful for model validation.

Daily mean correlation varies from station to station. Kirkeveien has the highest correlation of R^2=0.62 (2009) and Bygdøy has the lowest of R^2=0.23 (2010). The correlation indicates if the temporal variability is being correctly represented. This will depend both on the emission variability, due to temperature for wood burning and due to surface moisture for non-exhaust emissions, as well as the meteorological and dispersion conditions. Given the level of available data for calculating the emissions the modelled correlation, for PM_{10}, is considered to be quite high.

It is worth noting that the modelled non-exhaust emissions of PM_{10} make up around 33% of the concentrations at the monitoring sites Oslo, which are mostly traffic stations. Exhaust emissions contribute with 13%. Home heating contributes with around 7%. Regional background levels of PM_{10} are around 7.0 µg/m^3 and contribute with 32% of the total observed (Denby, 2013).

We conclude from the validation that the model, given the currently available input data, has an average bias of around -12% for the three years modelled and an uncertainty in the mean concentrations of between -20% and +5%. The error in the number of exceedance days is more significant. Based on the average absolute bias this error is between 30 – 50 %.

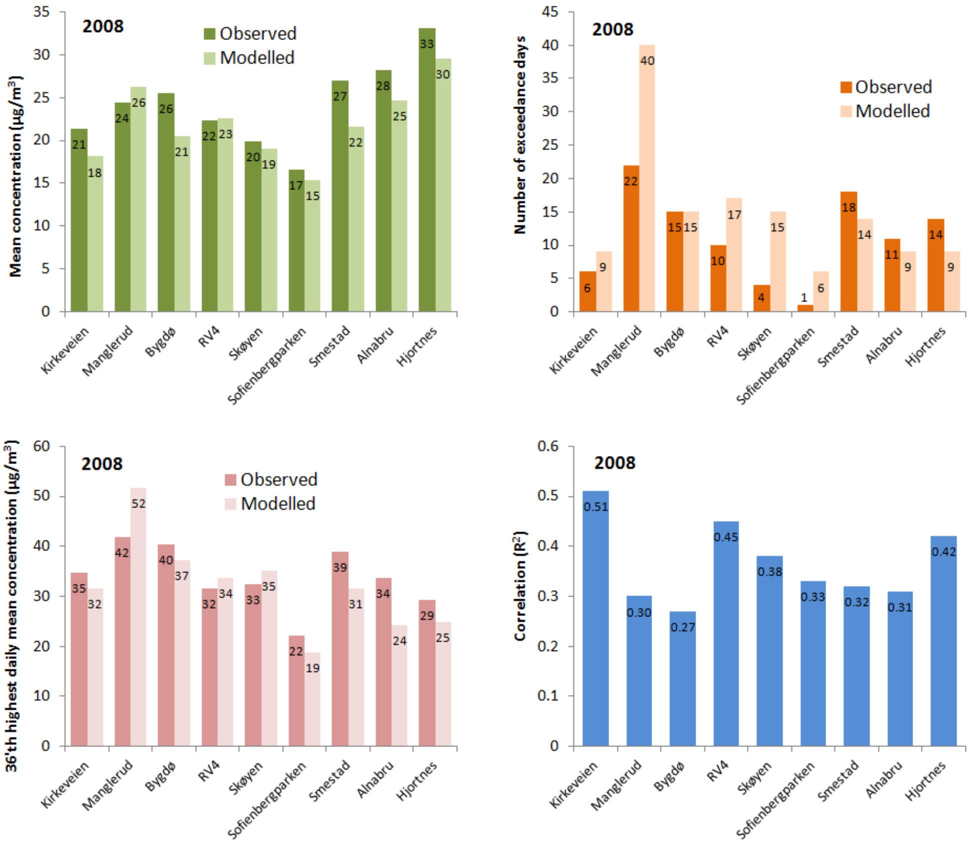


Figure 10: Calculated mean concentrations (left) and number of exceedance days, days with daily mean concentrations of PM_{10} > 50 µg/m^3, (right) for the year 2008 at 9 monitoring stations in Oslo. Model values presented are concurrent with available monitoring data.

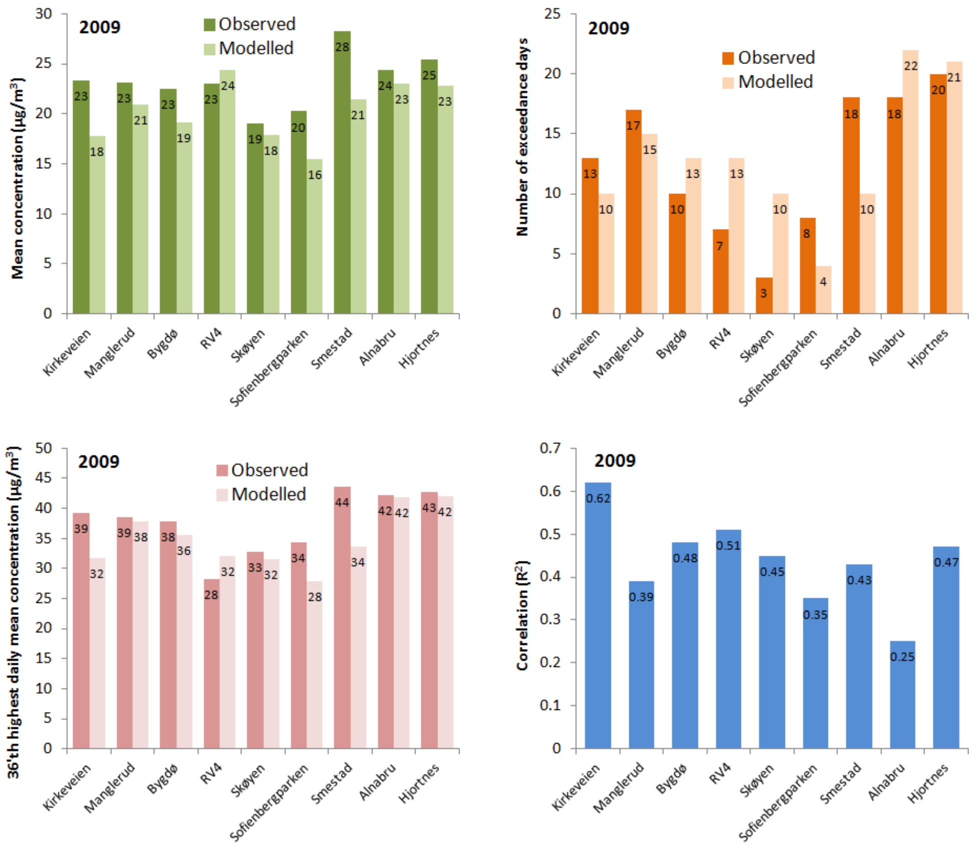


Figure 11: As in Fig. 10 but for 2009.

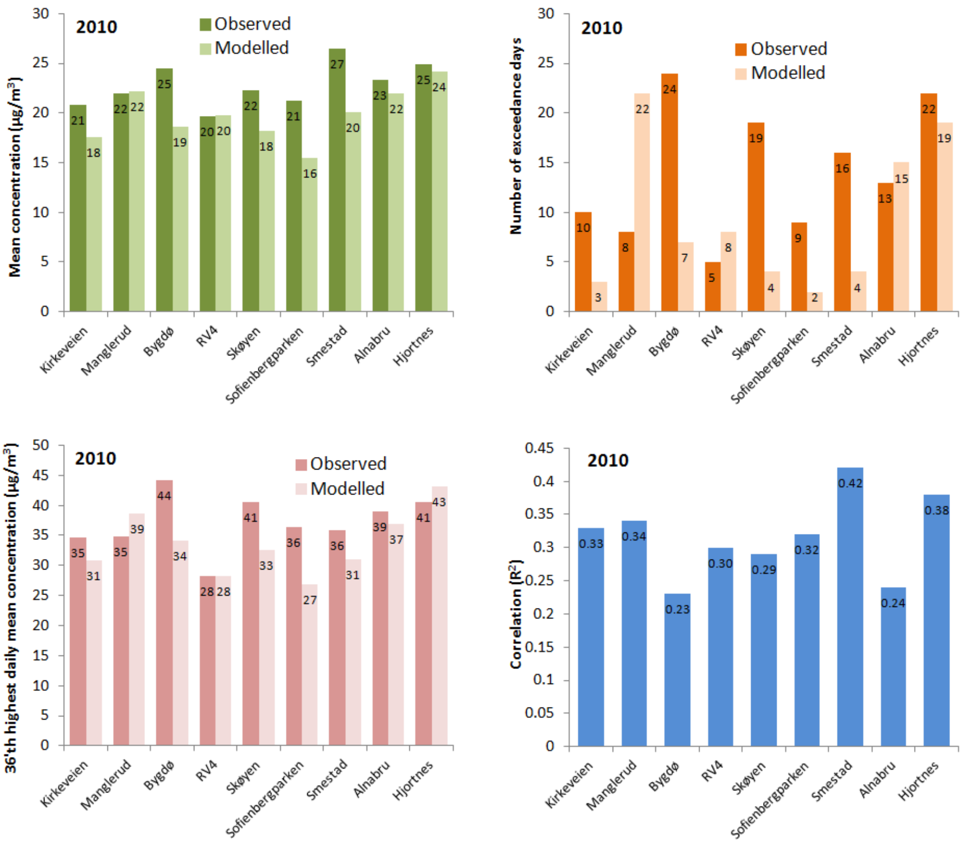


Figure 12: As in Fig. 10 but for 2010.

Since we are interested in the impact of the environmental speed limit we also summarise the results of the model validation for the four ESL sites (Manglerud, RV4, Smestad and Hjortnes) in Table 5. Here we see the same under prediction of annual means, by around 10%, but the average number of exceedance days at these sites is well modelled for the years 2009 and 2010. For 2008, the only year without cleaning, the modelled exceedance days are higher than observed. An additional, and important point for validation, is that the trend in annual means is correctly modelled from year to year.

Table 5: Summary of the model validation at the ESL sites using signed environmental speed limit (60 km/hr) as vehicle speed input to NORTRIP. Results are presented for each year as an average at the ESL sites Manglerud, RV4, Smestad and Hjortnes.

Period	**Modelled using signed speed limit**		**Observed**	
	Annual mean (µg/m³)	Exceedance days (days)	Annual mean (µg/m³)	Exceedance days (days)
2008	24.9	20	26.7	16
2009	22.4	15	24.9	15.5
2010	19.8	13.2	22.8	12.7
Average	**22.4**	**16.1**	**24.8**	**14.7**

4.3 Impact of the vehicle speed parameterisation

In this section we assess the impact of the vehicle speed parameterisation (Section 3.3) on the calculated concentrations. In Section 4.2 validation was carried out using vehicle speeds based on signed speed limits, as this was the method applied in Denby (2013). In Fig. 13 we present the change in the mean concentrations and the number of exceedance days when using the vehicle speed parameterisation. The comparison is for the entire modelling period and so not limited to periods when observations are available, as is the validation in Section 4.2.

The results indicate an increase in concentrations when using ‘realistic’ vehicle speeds. This is due to the fact that the modelled vehicle speeds are on average higher than the speed limits when speed limits are at the speed limit of 60 km/hr or lower. This is seen in the measured traffic speeds (Fig. 5) and is reflected in the modelled traffic speed parameters derived from these (Fig. 8). The average increase over all sites and years is < 1 $\mu g/m^3$, well within the uncertainty of the model, so it is not possible to state which of the traffic speed descriptions provides the better result. The importance of the modelled traffic speed is that it provides different sensitivities to changes in speed signage, as shown in Table 3.

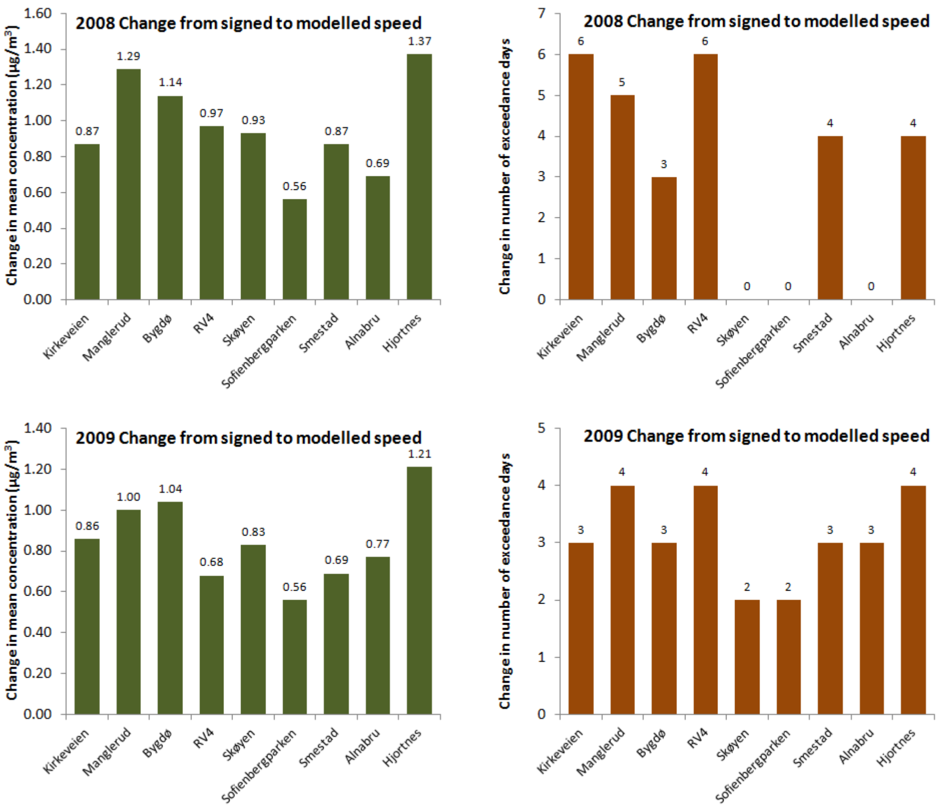


Figure 13: Changes in modelled PM_{10} annual mean concentrations (left) and number of exceedance days (right) for the three years 2008 (top), 2009 (middle) and 2010 (bottom). The change shown is the difference when going from signed speeds (speed limits) to the vehicle speed parameterisation (modelled speed). Environmental speed limit value is 60 km/hr in all these calculations.

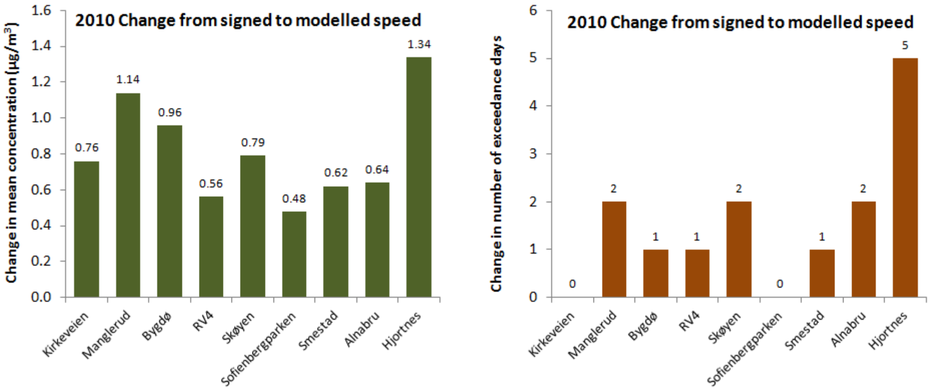


Figure 13: Contd.

Table 6: Summary of the difference in modelled concentrations when using the vehicle speed parameterisation instead of the signed speed limit as vehicle speed input to NORTRIP. Results are for an ESL of 60 km/hr and are presented for each year as an average at the four ESL sites Manglerud, RV4, Smestad and Hjortnes. All model data are used, not just data corresponding to observations, as in Table 5.

Period	**Using signed speed limit**		**Using vehicle speed parameterisation**		**Difference**	
	Annual mean (µg/m³)	Exceedance days (days)	Annual mean (µg/m³)	Exceedance days (days)	Annual mean (µg/m³)	Exceedance days (days)
2008	23.1	27	24.3	31.7	1.12	4.7
2009	20.4	15.5	21.3	19.2	0.89	3.7
2010	20.6	13.2	21.5	15.5	0.91	2.2
Average	**21.4**	**18.6**	**22.4**	**22.1**	**1.0**	**3.5**

4.4 Sensitivity to changes in the environmental speed limit

For all three years four separate calculations are carried out. These calculations use an environmental speed limit (ESL) of either 60 or 70 km/hr and for each of these speed limits the calculations are made using either the signed speed limit (SL) or the vehicle speed parameterisation (VSP), Section 3.3, as input to the NORTRIP model emission calculations. In all cases the environmental speed limit outside of the studded tyre season is set at 70 km/hr.

The resulting change in annual mean concentration and number of exceedance days, when going from and ESL of 60 to 70 km/hr, is shown for the 9 monitoring sites in Figs. 14 - 16. These are summarized as an average for the four environmental speed limit sites (Manglerud, RV4, Smestad and Hjortnes) in Table 7.

The maximum impact in the change of the ESL is found at the four sites placed along the ESL roads but the impact is also visible at other sites. This impact is roughly halved when using the vehicle speed parameterisation (VSP) compared to the signed speed limit (SL). This is a direct result of the lower sensitivity (factor 0.47, Table 3) of the VSP to changes in SL. On average we see that the change in speed from 60 to 70 km/hr will lead to a 1.5 – 3.4 % increase in annual mean concentrations and an increase of 8 – 19% in the number of exceedance days, where the range is indicative of the two different methods for determining vehicle speeds.

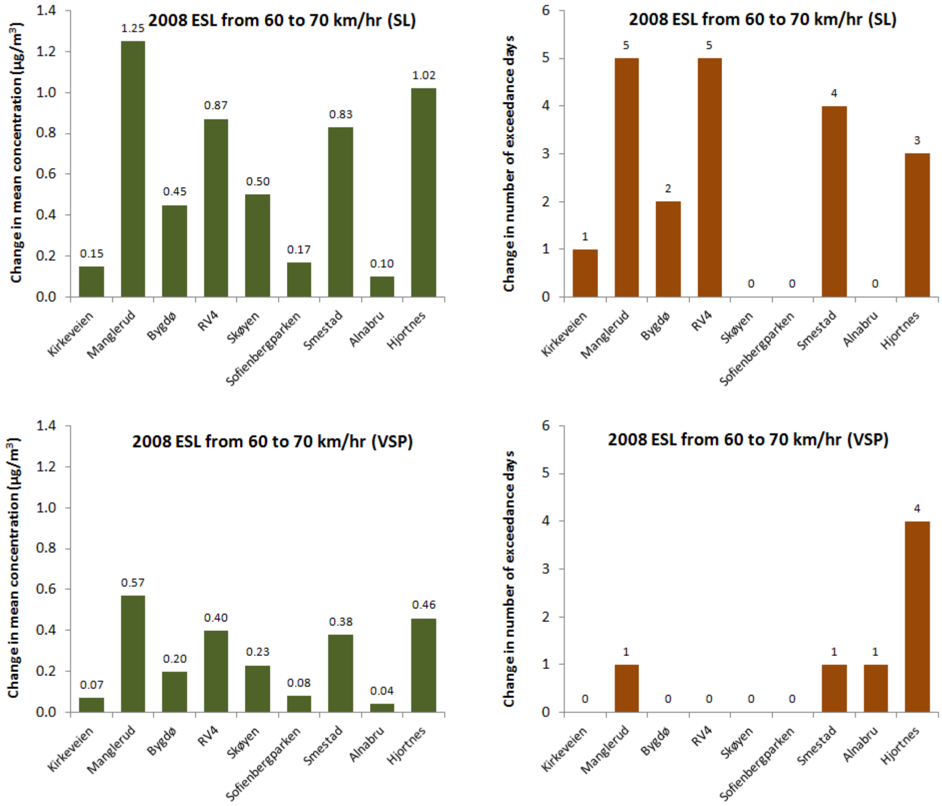


Figure 14: Changes in modelled PM_{10} annual mean concentrations (left) and number of exceedance days (right) resulting from an increase in environmental speed limit from 60 to 70 km/hr for the year 2008. Two different vehicle speed formulations are used. Top, using signed speed limits (SL) and bottom, using the vehicle speed parameterisation (VSP). Scales are the same in both upper and lower plots.

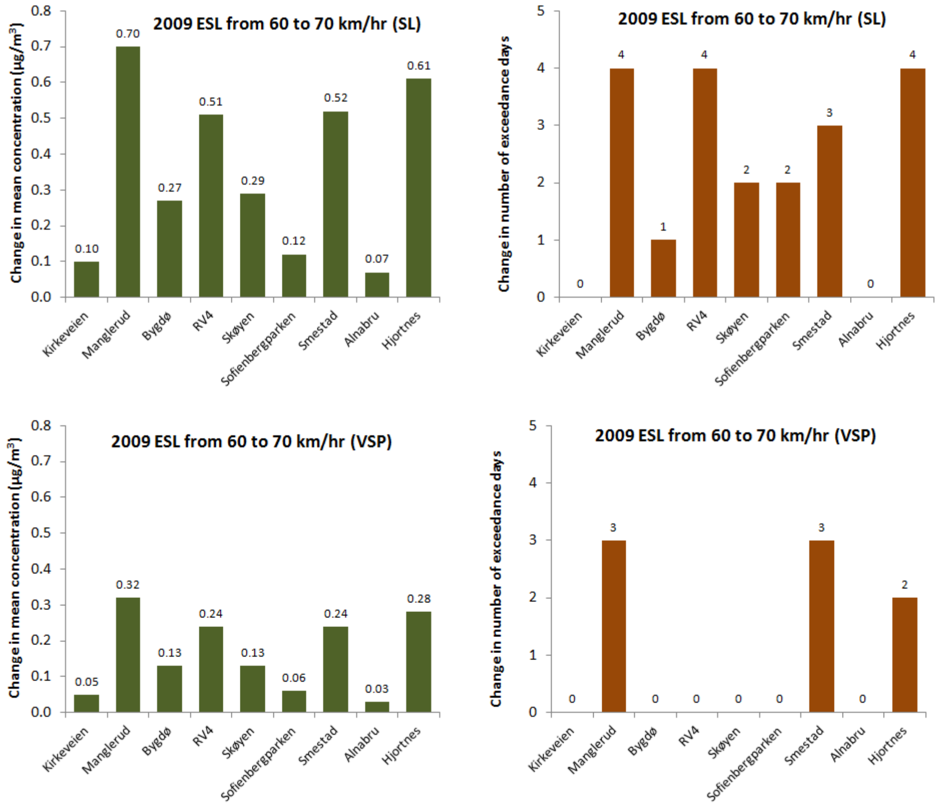


Figure 15: As in Figure 13 but for the year 2009.

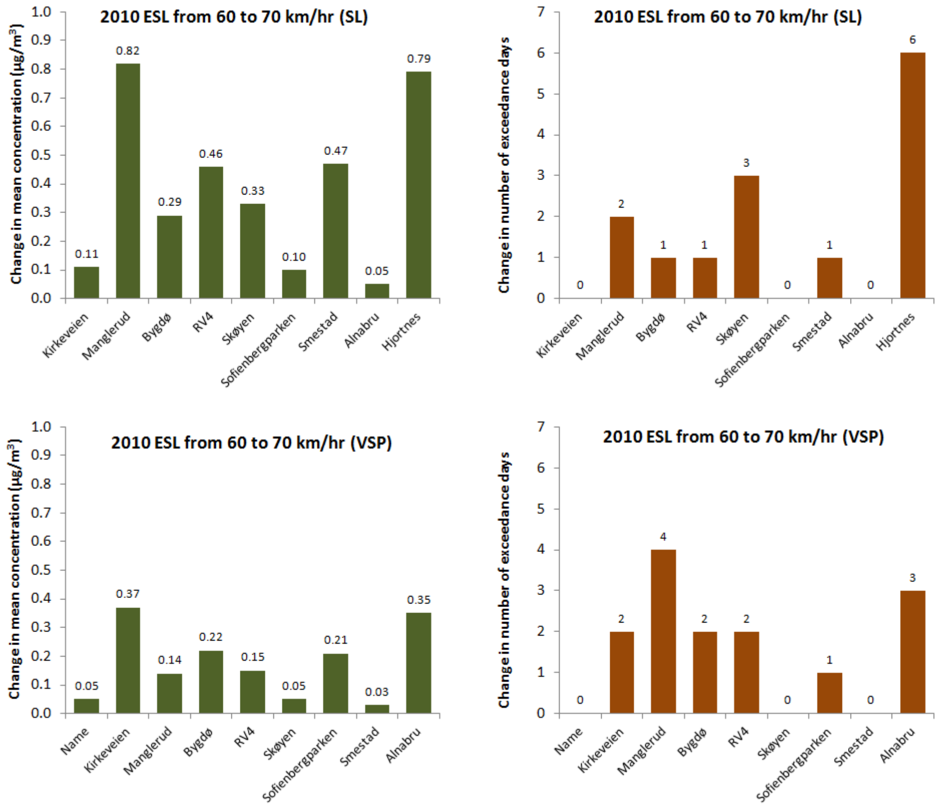


Figure 16: As in Figure 13 but for the year 2010.

Table 7: Summary of model calculations for the reference case (ESL of 60 km/hr, also shown in Table 6) and the change in model concentrations resulting from an increase in ESL from 60 to 70 km/hr. Shown are the two cases using signed speed limit or vehicle speed parameterisation as input to the NORTRIP model. Results are presented as an average at the ESL sites Manglerud, RV4, Smestad and Hjortnes. Note that the calculation period is for the entire year, not just for the periods when observations are available, as in Table 5.

Value	**Period**	**Using signed speed limit**		**Using vehicle speed parameterisation**	
		Annual mean (µg/m^3)	Exceedance days (days)	Annual mean (µg/m^3)	Exceedance days (days)
Reference calculation using ESL of 60 km/hr	2008	23.1	27	24.3	31.7
	2009	20.4	15.5	21.3	19.2
	2010	20.6	13.2	21.5	15.5
	Average	**21.4**	**18.6**	**22.4**	**22.1**
Change using ESL of 70 km/hr compared to reference	2008	1.0	4.3	0.45	1.5
	2009	0.59	3.8	0.27	2.0
	2010	0.63	2.5	0.29	2.0
	Average	**0.74**	**3.5**	**0.34**	**1.8**
Relative change	**Average**	**3.4%**	**18.8%**	**1.5%**	**8.2%**

4.5 Changes in the spatial distribution of PM_{10} concentrations

The change in emissions, resulting from a change in environmental speed limit, will be felt beyond just the monitoring stations. To present this we calculate PM_{10} concentrations, and changes in these concentrations, at spatially distributed receptor sites. These receptor sites represent aggregated home addresses at 100 x 100 m^2 resolution in Oslo. i.e. receptor points are placed at the population weighted centre of a 100 m grid. No receptors are placed where there is no population. This choice of presentation is intended to reflect the population exposure, rather than kerb side measurement sites, which is most relevant for health risk and assessment. However, a large number of these receptor points are also very close to roads.

We calculate annual mean concentrations and number of exceedance days at all these aggregated home address receptor points for the year 2008. The calculation makes use of the signed speed limit to calculate emissions from NORTRIP, thus giving the largest likely impact of a change in environmental speed limit. We present the total PM_{10} concentrations, for ESL = 60 km/hr, in Fig. 17. This map clearly shows higher PM_{10} concentrations surrounding major roads in Oslo. In addition heightened concentrations are seen near tunnel entrances. There are no receptor points in the map that exceed the annual mean limit value for PM_{10} of 40 µg/m^3.

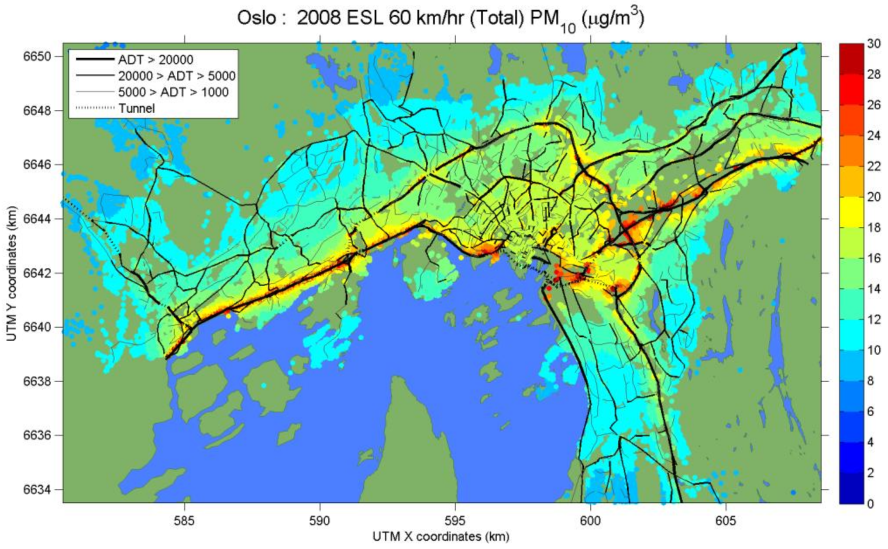


Figure 17: Annual mean PM_{10} concentrations calculated at aggregated home address receptor points for Oslo for the year 2008. Environmental speed limit for this case is 60 km/hr. Units are in µg/m^3.

In Figs. 18 and 19 we present the change in PM_{10} concentrations resulting from an increase is ESL from 60 km/hr to 70 km/hr, once again using the signed speed limit to calculate emissions from NORTRIP. These are presented as an absolute change in concentration (µg/m^3), Fig. 18, and as a relative change (%) in Fig. 19. In both of these figures the maximum colour coding corresponds to the highest 99.9% percentile.

The largest changes are seen near tunnel entrances but are generally concentrated around the ESL roads. Maximum increases in PM_{10} concentrations of around 1.5 µg/m^3, or 5%, are calculated. The monitoring sites at Manglerud and Hjortnes, with changes of 1.25 and 1.02 µg/m^3 respectively (Fig. 14), are representative of the higher impact areas in Oslo.

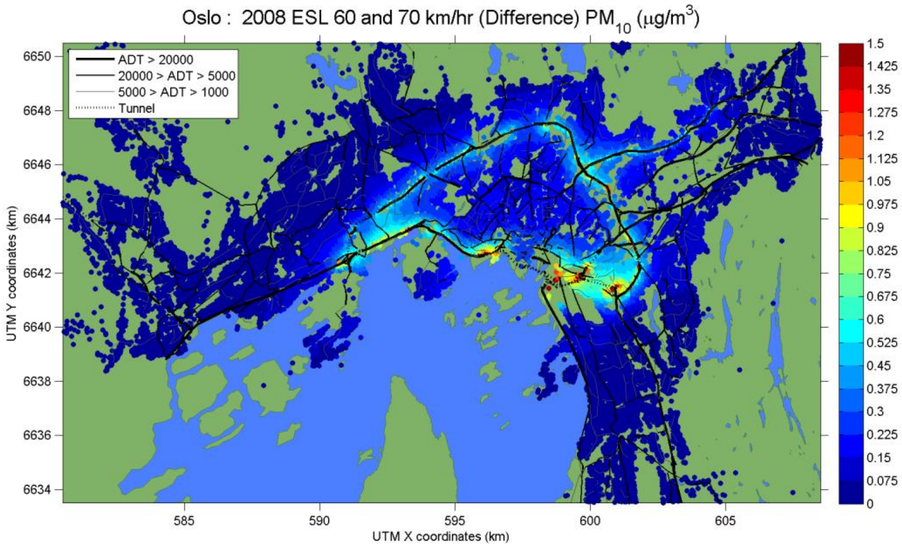


Figure 18: Absolute change in annual mean PM_{10} concentrations as a result of an increase in ESL from 60 to 70 km/hr, calculated at aggregated home address receptor points for Oslo for the year 2008. Units are in μg/m^3.

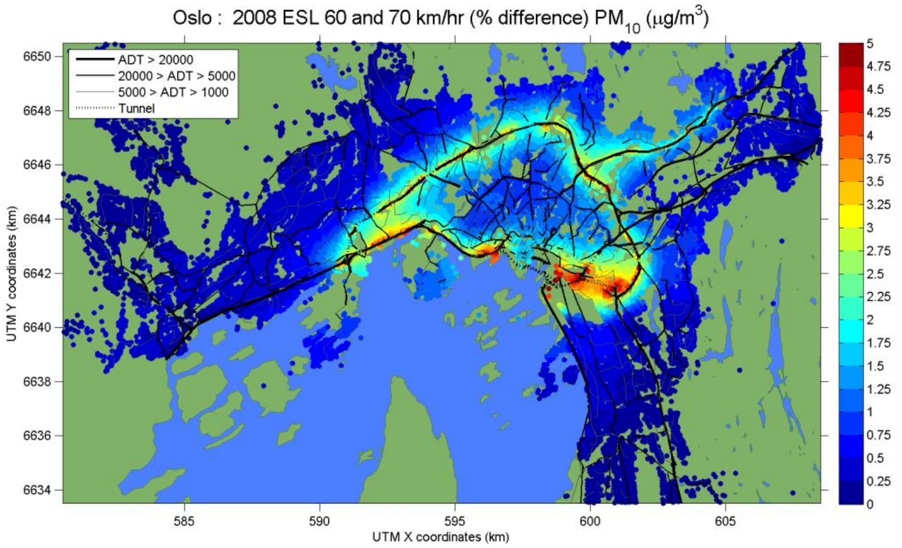


Figure 19: Relative change in annual mean PM_{10} concentrations as a result of an increase in ESL from 60 to 70 km/hr, calculated at aggregated home address receptor points for Oslo for the year 2008. Units are in percent (%).

The maximum change in concentrations near roads of around 5% can be inferred directly from the speed dependence used in the NORTRIP model. A change of speed from 60 to 70% is equivalent to an increase in road wear and suspension of 16%, due to the linear dependence of these factors on speed. In addition, the model source apportionment carried out (Section 3.2) shows that roughly 1/3 of the PM_{10} concentrations near roads are the result of non-exhaust emissions. This simple calculation indicates that the increase near roads due to the increase in ESL would result in a roughly 5% increase in concentrations, as is calculated by the model.

In Fig. 20 we show the spatial distribution of the number of exceedance days at the population based receptor points in two plots with different colouring levels. Exceedances are clearly concentrated around the road networks. The model calculates a number of areas to be in exceedance of the EU limit value (i.e. more than 35 days with $PM_{10} > 50$ µg/m^3), mostly near tunnel exists and in the most highly trafficked areas. The Norwegian national target values (no more than 7 days with $PM_{10} > 50$ µg/m^3) are exceeded extensively. We note however that for 2008 the model is seen to over predict (Table 5) exceedance days on average by 4 days at the ESL monitoring sites.

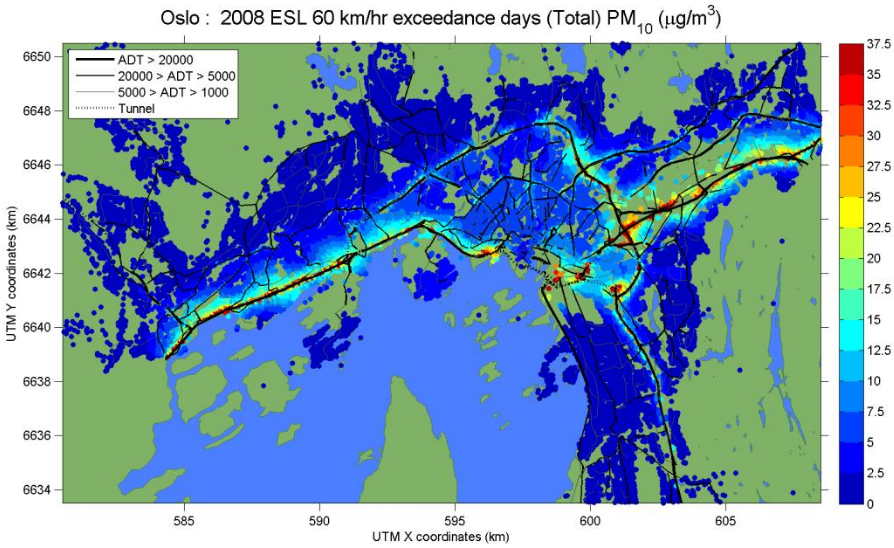


Figure 20: Number of exceedance days for daily mean PM_{10} concentrations calculated at aggregated home address receptor points for Oslo for the year 2008. Environmental speed limit for this case is 60 km/hr. Units are in days. The two maps show the same data but with different colouring. In the top plot all receptor points with the number of exceedance days > 35 are shown in dark red (corresponding to EU legislative limit values) whilst in the bottom plot all receptor points with the number of exceedance days > 7 are shown in dark red (corresponding to Norwegian national target values).

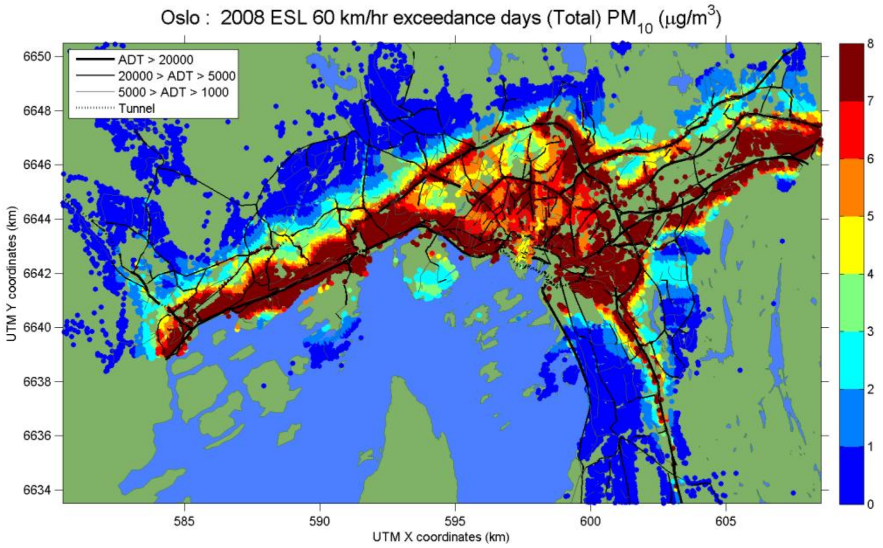


Figure 20: Contd.

In Fig. 21 we show the increase in the number of exceedance days when going from an ESL of 60 to 70 km/hr, using the speed limit as vehicle speed input to NORTRIP. Maximum increases of around 8 days are found but generally increases are less than 5. These plots show a significant amount of 'noise' since very small increases in concentrations can lead to changes in exceedance days when daily means are close to the limit value of 50 µg/m^3. No relative change is shown in the maps, as in Fig. 19, since large areas have no exceedances at all (Fig. 20).

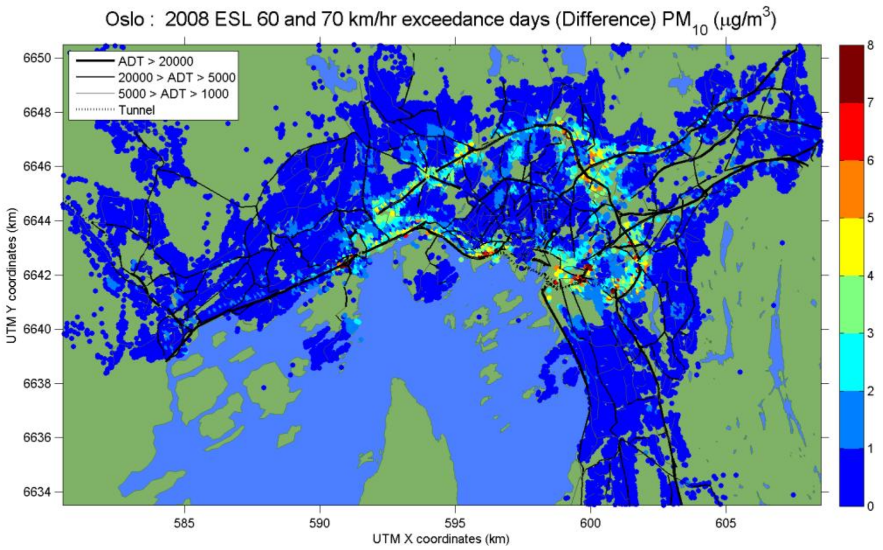


Figure 21: Absolute change in the number of exceedance days for daily mean PM_{10} concentrations as a result of an increase in ESL from 60 to 70 km/hr, calculated at aggregated home address receptor points for Oslo for the year 2008. Units are in days.

5 Summary and discussion

In this report we have applied the EPISODE dispersion model together with the NORTRIP road dust emission model to calculate PM_{10} concentrations for the years 2008, 2009 and 2010 in Oslo. The main aim of the study is to assess the impact of signed speed limit changes on the non-exhaust emissions from traffic. These changes have been applied to the environmental speed limit (ESL) roads in Oslo where signed speed limits are increased from 60 to 70 km/hr. Using the models we have investigated the sensitivity of the mean concentration and the number of exceedance days to changes in traffic speed along the ESL roads. This has been carried out at four ESL air quality monitoring sites for all three years and maps have also been produced to indicate the spatial distribution of PM_{10} concentrations and the impact of these changes for the year 2008.

5.1 Traffic data analysis

In addition to the air quality modelling, an assessment of measured traffic counts at three ESL sites has been carried out to determine the actual traffic speed and its dependency on the signed speed limit. Traffic counts carried out at the sites Manglerud, RV4 and Smestad for the years 2008, 2010 and 2012 have been analysed to assess vehicle speeds and their dependency on speed limit and traffic volume. The analysis indicates that a change in signed speed limit does not result in an equivalent change in average traffic speed. We find on average that a 10 km/hr change in signage will result in just a 4.7 km/hr change in traffic speed for these roads. This has important consequences for the emission of road dust since road wear and road dust suspension are assumed to be linearly dependent on traffic speed.

The traffic analysis has been generalised to provide a vehicle speed parameterisation that calculates hourly speeds for all major roads in Oslo based on the hourly traffic volume, the number of lanes and the signed speed limit. This parameterisation predicts higher traffic speeds than is indicated by signed speed limits, particularly for light trafficked roads with speed limits of around 50 – 70 km/hr. Though this parameterisation is found to be useful it does not take into account the impact of road network traffic flows and a traffic model would be required to predict these flows and speeds in a more realistic way.

5.2 Model validation

PM_{10} concentrations have been modelled for the years 2008, 2009 and 2010 in Oslo. The NORTRIP model, in a simplified form, has been used to calculate the contribution of non-exhaust traffic induced emissions. Modelled concentrations are compared to nine air quality monitoring sites in Oslo, four of which are traffic stations placed along ESL roads (Manglerud, RV4, Smestad and Hjortnes). Based on the model calculations the non-exhaust emissions account for 33% of the observed PM_{10} concentrations, when averaged over the nine available monitoring sites.

Comparison with observations over the three years indicates an average model fractional bias of -12% with a total range of -30% to +10% for the individual stations, including the ESL sites. The model tends to under predict concentrations mostly in the summer where other emissions sources, e.g. windblown suspension or organic contributions, may be missing.

The model error in predicting the number of exceedance days is larger than that found for the mean concentrations, with the model over predicting the total number of exceedance days for all sites by 17% but with an uncertainty for an individual site, based on the absolute bias per station, of approximately 40%. The number of exceedance days can be very sensitive to slight variations in daily mean concentrations and is a poor indicator for model validation purposes. We find, however, that the average number of exceedance days at the four ESL sites well represents the observations for 2009 and 2010 at 15.5 and 12.7 days respectively. For 2008 the model over predicts the number of exceedance days by 4 days (Table 5) where the observed average is 16 days.

Maps of annual mean concentrations and number of exceedance days made for the year 2008 indicate that there are unmonitored areas in Oslo where higher concentrations and exceedances of daily mean limit values occur, than those already observed. Though mapping of exceedances was not an aim of this study, the maps indicate that further assessment is required.

5.3 Sensitivity to the environmental speed limit

A sensitivity test is carried out where speed signage on ESL roads is increased from 60 to 70 km/hr, whilst keeping the summer speed limit to 70 km/hr. The impact of this change of speed is assessed in two ways. Firstly by assuming that the actual traffic speed also changes by 10 km/hr and secondly that the actual traffic speed changes more realistically by just 4.7 km/hr, using the vehicle speed parameterisation developed from traffic counts. The results, shown in Table 7, indicate that annual mean PM_{10} concentrations (assessed at the four ESL sites) increase by an average of 0.74 $\mu g/m^3$ (3.4%) for the first case and by 0.34 $\mu g/m^3$ (1.5%) for the second case. Similarly the average number of exceedance days increases by 3.5 (19%) and 1.8 days (8%) for the two cases (Table 7).

5.4 Comparison to other road dust reduction measures

Sensitivity tests of the model, carried out for 2009 in the previous linked report (Denby, 2013), show that a reduction in the number of vehicles using studded tyres by 1% for LDV and by 0.5% for HDV leads to a reduction in mean concentrations at the ESL sites of 0.25 $\mu g/m^3$, which is roughly 1.3% of the total mean concentrations. The same 1% change in the studded tyre usage also leads to an average change of 0.8 exceedance days (10.5%). These results are calculated for a studded tyre share of 16% for LDV and 8% for HDV. This means that a 1.5% to 3% reduction in vehicles using studded tyres would be equivalent to the reduction obtained by reducing the winter time speed limit from 70 to 60 km/hr. The range reflects the differences in the way speed limit changes affect actual speed, as presented in this study. However, since studded tyre share reductions impact on every road, compared to ESL which is limited to just some major roads, then the improvement obtained by reducing studded tyres will have a much wider spatial impact.

The sensitivity of the model to the number of heavy duty vehicles (HDV) was also assessed in the report from Denby (2013) for 2009. According to those results a reduction in the number of HDV by roughly 10% would also lead to a comparable decrease of 2% in the annual mean concentrations and a reduction in the number of exceedance days of around 8%.

The impact of cleaning was also assessed in Denby (2013) but these results likely overstate the reduction obtained through cleaning since for 2009 the number of cleaning events, given from ISS data, was 20. Together with an assumed cleaning efficiency of 20% this reduced the road dust loading significantly in the months February - March. It was found that use of these cleaning data lead to a reduction in mean concentrations of 13% and a reduction of the average (all 9 stations) number of exceedance days by 60%. This makes efficient cleaning a potentially effective method for reducing road dust emissions. However, this is very uncertain and requires more information before cleaning can be properly quantified using the model.

5.5 Uncertainties and meteorological variability

Though meteorology was held fixed for the sensitivity tests in this report the previous report (Denby, 2013) indicated significant variability in PM_{10} concentrations for RV4 calculations as a result of differing meteorology and road maintenance activities. The typical observed difference in annual mean and number of exceedance days, at the four ESL sites, for the years 2008, 2009 and 2010 is found here to be 2.2 μg/m^3 and 2.3 days respectively, based on the absolute mean difference between these years. This makes inter-annual variability of annual mean concentrations significantly larger than the impact of the change in the environmental speed limit. This is similar to the findings in Denby (2013) where different meteorological conditions had as significant an impact on concentrations as did changes in traffic conditions for the site RV4 in the years 2004 - 2006.

In addition to the variability in the meteorology we also see that annual mean regional scale background concentrations can vary by a similar amount, approximately 2 μg/m^3 (NILU, 2012), making direct inter-annual comparisons difficult. For the years 2008 – 2010 presented here the regional background concentrations varied by less than 0.4 μg/m^3.

Uncertainty of the total model results has been assessed by comparison with the available monitoring data which indicates levels of uncertainty in mean concentrations at individual sites from -20% to +5% and in the number of exceedance days of around 40%. These total model uncertainties are thus also higher than the expected impact of ESL speed changes. However, there is a difference between total uncertainties and uncertainties in model sensitivities. If we assume that the NORTRIP model correctly represents the speed dependence of road wear and road dust suspension (linear relationship) then the eventual uncertainties in the changes in concentration due to a change in speed will be similar to the relative sensitivities of the total model calculations. This then makes the uncertainty in the model sensitivity less than the uncertainty in the actual traffic speeds which are used as input.

5.6 Concluding statement

By taking into account uncertainties in model calculations, in traffic speeds and in inter-annual variability we conclude that the impact on air quality due to an increase in environmental speed limit from 60 km/hr to 70 km/hr is in the range from 0.3 to 0.8 $\mu g/m^3$ for the annual mean concentrations and from 1.5 to 4.0 days for the average number of exceedance days. This result is valid for the ESL monitoring sites addressed in this study. Spatial assessment indicates that the impact can be larger at other ESL sites, by up to a factor of two.

Population exposure was not directly addressed in this study, but it should be noted that a change of up to 4 exceedance days is considerable when compared to the Norwegian national target of 7 allowed exceedance days. From a health perspective there is no lower concentration threshold bellow which no health impacts can be observed for particulate matter and so all reductions in concentrations will lead to health benefits, especially in densely populated areas such as Oslo.

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TITLE Modelling non-exhaust emissions of PM10 in Oslo: Impact of the environmental speed limit using the NORTRIP model	PROJECT LEADER Bruce Rolstad Denby NILU PROJECT NO. O-113106: Speed
AUTHOR(S) Bruce Rolstad Denby Ingrid Sundvor	CLASSIFICATION * A CONTRACT REF.

QUALITY CONTROLLER: Cristina Guerreiro

REPORT PREPARED FOR
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ABSTRACT
This report was requested by the Norwegian Public Roads Administration (Statens vegvesen) to provide information concerning non-exhaust traffic emissions in Oslo and the impact of changes in environmental speed limits on these emissions. This report provides the results of calculations made with the dispersion model EPISODE coupled to the NORTRIP road dust emission model, a recently developed emission model for calculating non-exhaust emissions. The change in modelled emissions due to changes in environmental speed limit are calculated for two different speed scenarios, where 'speed limit' and 'realistic speed' changes are compared. In addition the impact of the environmental speed limit is compared to other road dust control measures involving studded tyre share and heavy duty vehicle reduction, taken from a previous report.

NORWEGIAN TITLE
Modellering av ikke eksosutslipp av PM_{10} i Oslo: Påvirkning av miljøfartsgrensen ved bruk av NORTRIP-modellen .

KEYWORDS		
Air Quality	Modelling	Aerosols and particles

ABSTRACT (in Norwegian)
Denne rapporten er utført på oppdrag fra Statens vegvesen for å gi informasjon om ikke-eksosutslipp i Oslo og effekt av endring i miljøfartsgrensa. Rapporten viser beregningsresultat fra spredningsmodellen EPISODE med bruk av den nyutviklete utslippsmodellen NORTRIP for å beregne veistøvutslippet. Endret utslipp er beregnet av modellen med to ulike hastighetsendringer, skiltet hastighet og reel hastighet. I tillegg er effekt av miljøfartsgrensa sammenlignet med andre støvreduserende tiltak, som redusert piggdekkandel og mindre tungtransport, fra beregninger som var utført i tidligere arbeid.

** Classification*	*A*	*Unclassified (can be ordered from NILU)*
	B	*Restricted distribution*
	C	*Classified (not to be distributed)*

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